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SURGE PROTECTION OF LOW-TENSION OVERHEAD LINES

by J. W. G. MULDER.

Summary. In this article the requirements for an efficient protection of overhead low-tension transmission lines against excess voltages and surges are discussed. The construction and method of operation of the Philips lightning arrester are described.

Introduction

Overhead power lines which are used for transmission purposes in nearly all countries are comparatively frequently exposed to excess voltages created by electrical phenomena taking place in the atmosphere. The probability of a transmission line being directly struck by lighting is not very great; but it is by no means exceptional for these lines, which possess a certain capacity with respect to earth, to become charged by atmospheric effects to a potential under which the weakest parts of the insulation of the associated installations must necessarily fail. Since the insulators from which the lines are suspended are usually adequately rated to withstand high excess voltages, it is frequently the coils in the electricity meters and the insulation of the house connections, etc., which suffer when a surge is experienced.

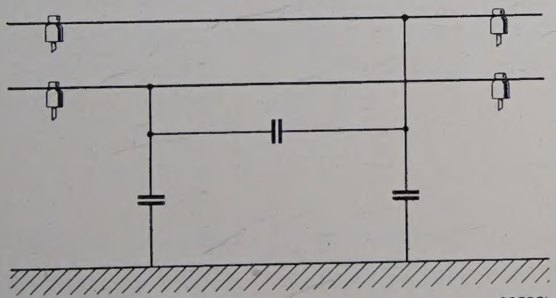


Fig. 1. Equivalent circuit of an overhead line.

Over-voltages may also be produced by electromagnetic induction when powerful surges occur in neighbouring conductors, such as metal masts and trees, when these are struck by lightning. Travelling waves are then produced which are liable to damage the insulation and the whole of the plant connected to the network.

In low-tension networks, over-voltage conditions can be initiated by a host of causes other than atmospheric discharges, as for instance, high short-circuit currents in adjoining high-tension lines, or by the impulses sustained on switching heavy loads, etc. But since excess voltages due to these causes are far less powerful than those due to atmospheric causes, they will not be discussed in this article, particularly as it may be assumed that the whole of the insulation has been suitably adapted to withstand these abnormalities of non-atmospheric origin.

Intensity of Lightning Flashes

The magnitude of the discharge currents occurring in lightning strokes has been investigated in some detail in reference to high-tension transmission networks. Various methods are used for measuring the intensity of these currents; thus the diameter of the puncture produced by the discharge current in a thin sheet of paper held between two metal plates can be measured and the corresponding current intensity found by calibration. Better results can be obtained with magnetisable steel needles; in this method the maximum magnetic field intensity which has been applied to a needle is determined by measuring the magnetism remanent in the needle after it has been left near a high-tension pole; this measurement is independent of the duration of the field. The maximum value of the discharge current can then be calculated for the particular arrangement used from the maximum

magnetic field intensities measured at the location of the needle.

Mc Eachron and Mc Morris [1]) used this method for recording 156 positive and 255 negative discharge currents at 1225 different points. Of these 411 recorded discharge currents 0.73 per cent. were found to be above 15 000 amps, the maximum intensity measured being 17 000 amps. These investigators also calculated from their measurements the probability of lightning discharges occurring with intensities above a specific limiting value. Naturally this probability decreases very rapidly as the intensity increases, as may be seen from *fig. 2* which shows the time intervals at which a

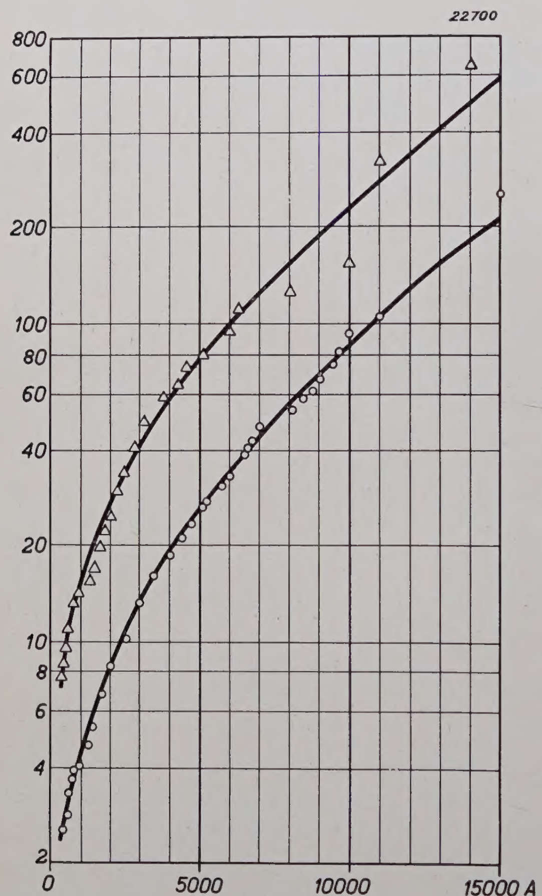


Fig. 2. Time in years in which a single discharge in one needle above a certain current intensity may be expected to occur, plotted against the current intensity (according to Mc Eachron and Mc Morris). The upper curve refers to an urban and the lower curve to a rural district.

discharge above a certain current intensity may be expected in one needle within a given area.

A systematic investigation of atmospheric discharges is clearly both cumbersome and tedious, for the occurrence of these discharges depends largely on fortuitous circumstances. During the last few years, however, a mass of observational data has been collected and correlated both in the United States by the Franklin Institute and in Switzerland. It is found that the intensity of these discharge currents covers a very wide range and also that current intensities considerably higher than the values stated above are possible even in Europe. An intensity of 30 000 to 60 000 amps is by no means exceptional, and in isolated cases currents up to even 100 000 and 200 000 amps may be encountered. Under the auspices of the Dutch Standards Institution, a committee was set up to make recommendations regarding the precautions necessary as a protection against lightning. This committee will shortly publish the results of its investigations. The vast amount of data which has been collected and classified, considerably amplifies our understanding of the generation and effects of lightning discharges as compared with the state of knowledge of a few years ago. One of the tasks of the committee has been the preparation of a map showing the nature and distribution of lightning strokes in the Netherlands over a certain period. This map shows that the distribution of the strokes is by no means arbitrary, but that in certain regions the probability of lightning strokes causing damage is much greater than in others. It has thus been shown, in confirmation of everyday experience, that the danger of lightning strokes is particularly severe in the neighbourhood of rivers and in places where the subsoil water levels are high. According to the experience of the electricity authorities, an exceptionally high percentage of discharges on overhead lines takes place in just these areas. Various places, such as isolated farms and the terminations of overhead lines, frequently have the reputation that the associated electricity meters become damaged at regular intervals, for instance, monthly.

Precautionary Measures

For many years, attempts have been made to protect overhead lines by equipping them with devices for conducting the excess voltage to earth. These devices have to meet extremely severe specifications, and it was soon found that the horn arresters (*fig. 3*) originally used did not provide an altogether adequate safeguard. Although quite able to deal with surges of the intensities in question while their shape facilitated the extinction of the power arc, the initial breakdown voltage of these

[1]) Mc Eachron and Mc Morris: Discharge currents in distribution arresters. El. Eng., **54**, 1395 - 1399, December, 1935.

[2]) Other protective devices such as condensers and damping circuits are not discussed in this article.

arresters yet proved to be too high. The distance apart of the two poles of the spark gap had in fact to be made so small that a flashover occurred at potentials which were below those liable to damage the connected meter coils. Moreover, any dirt accumulating could readily cause a short circuit between electrodes situated so close together, so that it became customary to make the gap between the electrodes much greater than was desirable for low initial breakdown. Since with the majority of spark gaps the flashover takes place with a certain delay both in air and rarefied gases, the socalled dynamic breakdown voltage and not the static breakdown voltage has to be taken into consideration here.

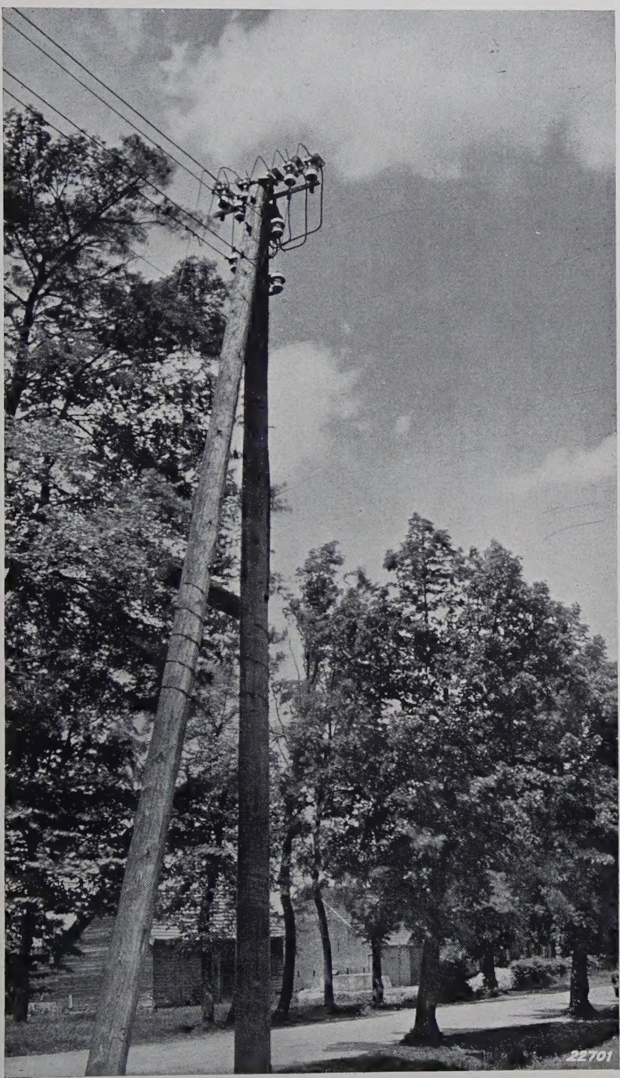


Fig. 3. Method of mounting horn arresters; these are always fixed above the pole to allow the arc to travel upwards out of the horns.

The definition of the dynamic breakdown voltage implies that a certain time interval is required for the discharge to be built up. Hence, with a particular spark gap, the breakdown voltage is the higher the shorter the time the potential in question is applied to the electrodes. The lowest breakdown voltage is thus observed with direct voltages by the static method, while for potentials subject to rapid fluctuations, as with a steep-fronted surge wave, much higher values are encountered by the dynamic method. But a certain time must also elapse to puncture the insulation of an electrical installation. An essential characteristic of an efficient lightning arrester is therefore that the dynamic breakdown voltage of the arrester is lower than that of the insulation which has to be protected and which is in parallel to it (*fig. 4*).

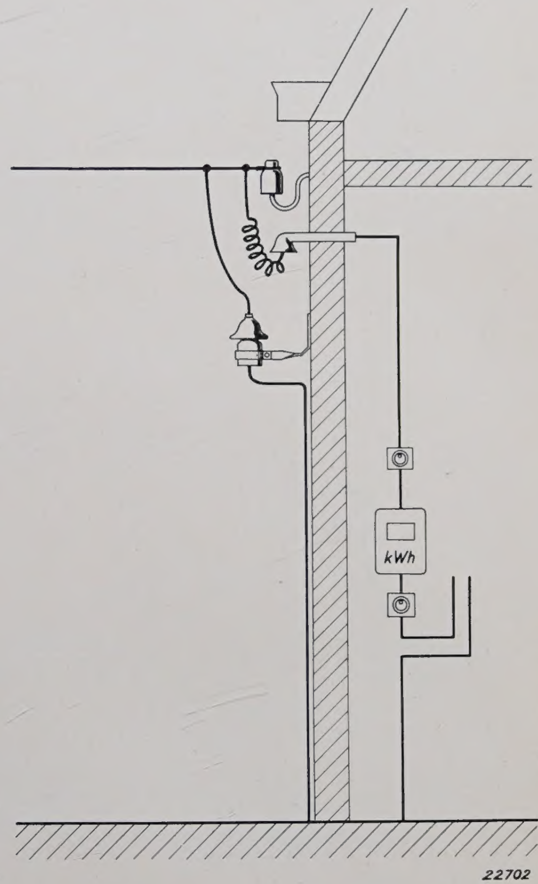


Fig. 4. Circuit of a house installation incorporating a lightning arrester.

But horn arresters operate with a considerable inertia and in fact only respond rapidly to very high voltages; the protection provided for the insulation of the connected installations and plant is thus inadequate.

Another requirement is that the discharge must be automatically extinguished in the lightning arrester as soon as the over-voltage wave disappears. The voltage at which the discharge in the arrester collapses, i.e. the extinction voltage, must, in consequence, be made as high as prac-

ticable, in any case much higher than the mains voltage.

The principal requirements of an efficient arrester are therefore:

a) Low dynamic breakdown voltage,
b) Capacity for handling large discharge currents, and
c) Sufficiently high extinction voltage.

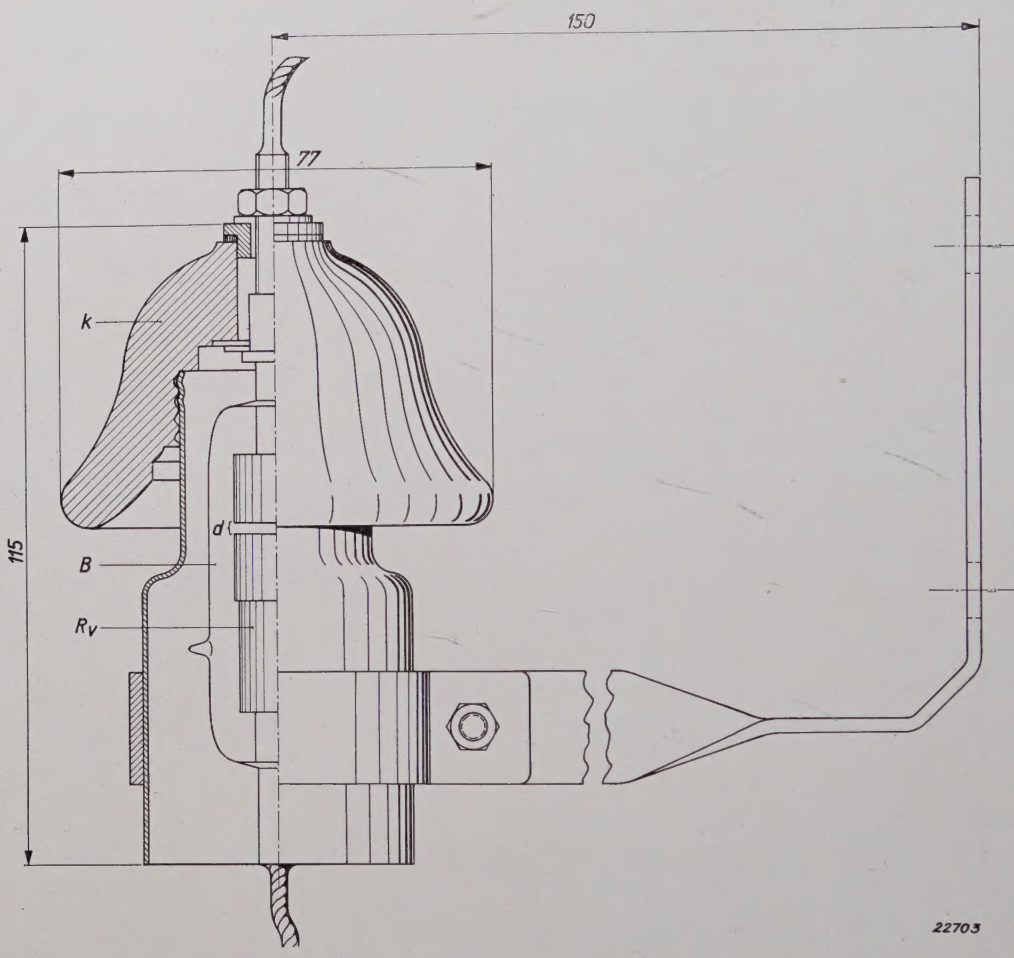


Fig. 5. Section through a Philips lightning arrester (type 4394) for low-tension networks, with dimensions given in mm. A hood K protects the discharge tube B against rain. The discharge gap d is located between two heavy iron electrodes. R_v is the series resistance.

Characteristics of Lightning Arresters

a) and b) are determined from the characteristic curves which can be plotted with an impulse-voltage generator and a cathode-ray oscillograph:

1) A current-voltage curve with a surge of specific wave front gradient and duration;
2) A socalled "protection characteristic" ($V=f(V_l)$) which indicates the limiting voltage V which is produced at a certain point of an arrester when a surge with a peak value V_l arrives from a distance which is large as compared with the length of the impulse. This voltage is determined for a certain impedance of the line (e.g.

$$Z = \sqrt{\frac{L}{C}} = 500 \text{ ohms})$$

and is usually measured at one end of the line; as a rule a steeper wave front is used than when plotting the current-voltage characteristic.

Permissible Loading

b) and c) are determined by loading tests in which the conditions of test are closely specified, and which *inter alia* must not appreciably alter the form of the characteristics in question. Since, as we shall see, extinction is determined by the temperature of the electrodes, a certain number of loading impulses must be applied at prescribed intervals; at the same time an alternating voltage of 50 cycles (1.2 to 1.5 times the mains voltage) is applied to the arrester. If required the loading impulses can be synchronised with the most dangerous point on the low-frequency voltage phase.

In addition to the above, the arrester has also to satisfy the following requirements:

d) The breakdown voltage at 50 cycles must be

much higher than the normal voltage (e.g. more than twice the latter) and in fact so high that the arrester does not respond to the highest normal excess voltages.

e) The insulation of the arrester for low-tension networks must be able to sustain safely an over-voltage of 3 000 volts at 50 cycles, when the spark gap is removed and the insulator is exposed for 5 minutes to a water spray of 3 mm per minute impinging at an angle of 45 deg.

f) Its mechanical construction must be sufficiently robust to reduce as far as possible the danger of a permanent short or earth when the device is damaged and an overload is applied.

Official Test Specifications

Official specifications of tests for lightning arresters have not yet been formulated in any country. It is obvious from the data given above regarding the intensities which may occur with lightning discharges that devices capable of withstanding a direct stroke would prove far too costly for adoption on a large scale. Since many thousands of lightning arresters are required and must be located at comparatively short distance apart along the lines, no attempt has been made to provide adequate protection against a direct stroke.

In Germany the Verein deutscher Elektrotechniker (V.D.E.) and in the Netherlands the Keuringsbureau van Electrotechnische Materialen van de Vereeniging van Directeuren van Electriciteitsbedrijven ("inspection and testing bureau for electro-technical materials of the directors of the electrical power stations" or "Kema") have drafted specifications which at the present time are being examined as regards their practical suitability. The two drafts differ in a number of essential points, the principal differences being in regard to the extinction voltage required, whether synchronisation in the extinction test is desirable or not, the number of loading impulses required and the most suitable intervals between successive load tests, and the form of the impulse wave to be used. It should be pointed out that the results of a test depend largely on the form of the wave.

The three principal requirements, viz., of a low dynamic breakdown voltage, large discharge capacity and a high extinction voltage, are not simultaneously promoted to the same extent by the majority of design factors, so that the practical compromise which is arrived at depends on which of the three desiderata is regarded as the most important one.

The Philips lightning arrester for low-tension networks of the type described in this article has an adequate extinction voltage (1.25 × working voltage) and as low as possible a dynamic breakdown voltage (1 500 to 3 500 volts, with an average of 2 400 volts found in tests on 123 specimens).

Modern Arresters

Considerable advances have been made in recent years in the construction of efficient and suitable lightning arresters, and these are now gradually replacing the obsolete horn arresters. The experience gained with these modern types of arresters has been satisfactory, and there has been a marked reduction in the number of faults sustained in the overhead lines of low-tension networks equipped with such arresters. From this it may be concluded that these devices are reliable in service, and in consequence, they are being installed in steadily-growing numbers in feeder networks.

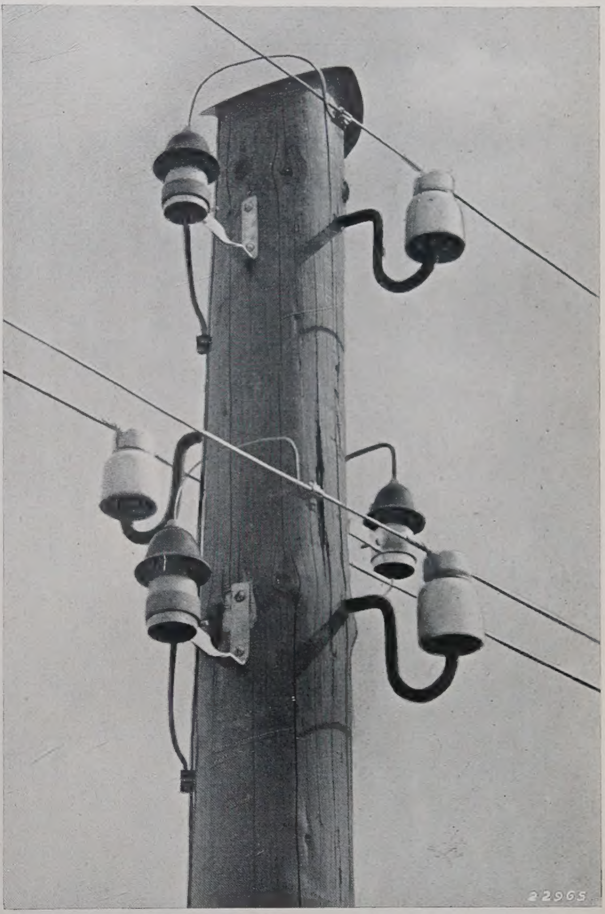


Fig. 6. Showing how the lightning arrester is mounted; it is no longer necessary to place it above the pole or mast, which thus makes the arrangement more compact and easier to inspect than with horn arresters.

A description of a lightning arrester manufactured by Philips for low-tension networks is

given below, with detailed reference to its main characteristics.

Philips Lightning Arrester

A section through the Philips lightning arrester is shown in *fig. 5*. The porcelain hood K provides the necessary protection against rain to allow the arrester to be mounted in the open. Below this

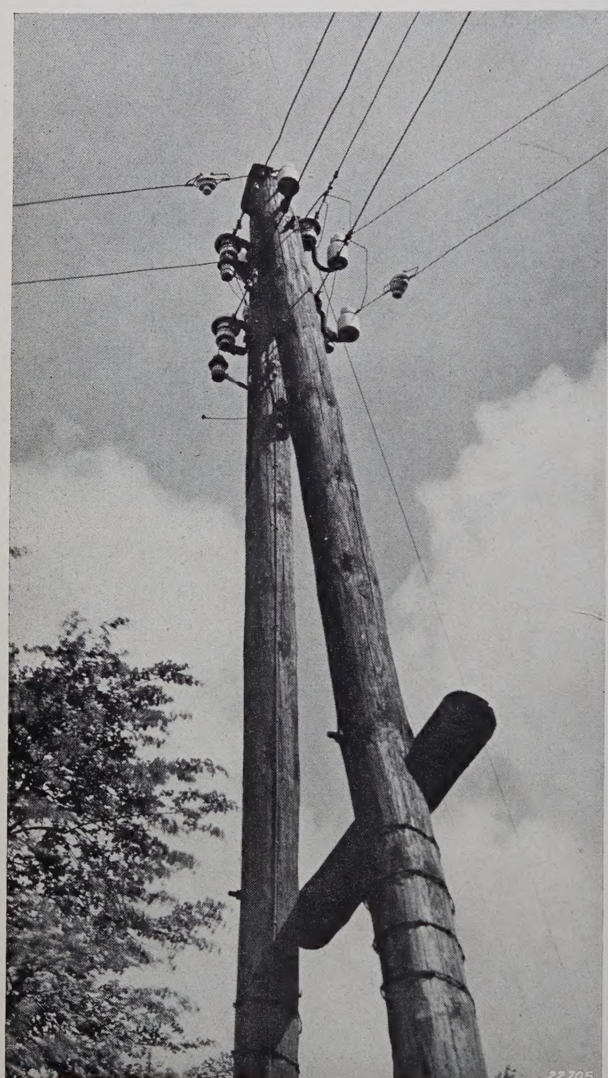


Fig. 7. Low-tension lines safeguarded with one of Philips lightning arresters. This terminal pole was exposed to an abnormal danger from lightning strokes, according to practical experience, before the arresters were installed. The arrester on the left under the insulators has failed; one of its electrodes is suspended by a wire and is visible from a considerable distance.

hood is a hermetically-sealed discharge tube B filled with gas at a low pressure and enclosing a discharge gap d. A resistance R_v is connected in series with G. Constancy of the discharge gap and the resistance are ensured, irrespective of changes in atmospheric conditions, by enclosing these two components in a sealed chamber. This is important, as the properties of these components to a large extent determine the dynamic breakdown voltage and the extinction voltage.

To avoid high self-inductances, loops and bends are avoided as far as possible in the leads connecting the arrester to the feeders and to the earth lead (cf. *fig. 6*). The resistance of contact of its earth connection should be made as small as possible by care in making joints.

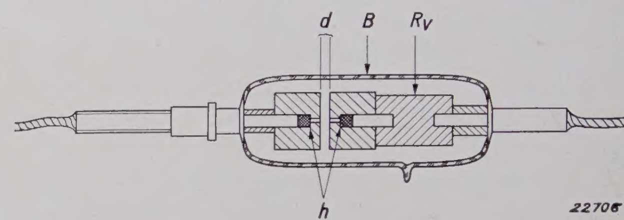


Fig. 8. Section through the discharge tube B. d is the discharge gap and R_v the series resistance. The recesses h contain substances from which alkali metals are liberated on heating.

A useful characteristic of this type of arrester, to which attention must be called, is that if the device is directly struck by lightning the glass tube is destroyed, which allows the lower electrode to drop and hang suspended from the connecting wire in a conspicuous position. This feature, as may be seen from *fig. 7*, considerably simplifies the location of damaged arresters.

Properties of the Discharge

A detailed discussion of the vital component of the arrester, viz., the discharge gap, will now be given. The discharge tube is shown in section in

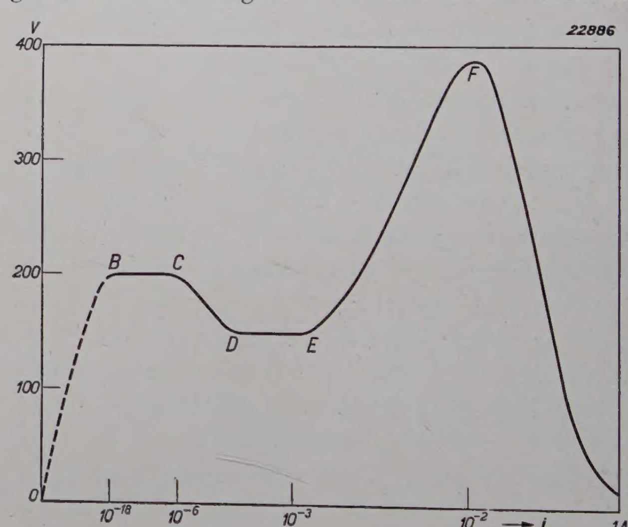


Fig. 9. Diagrammatic characteristic of voltage and current with a discharge between two parallel plates.

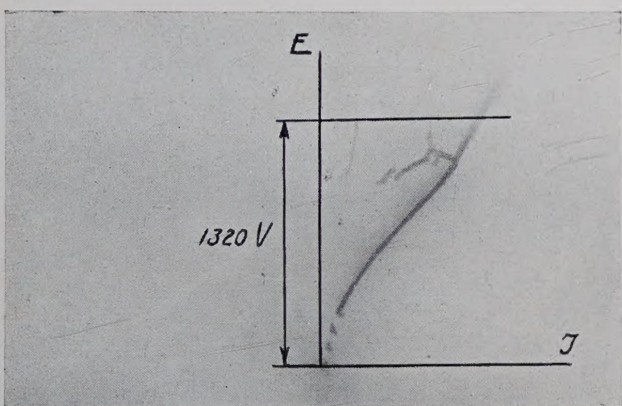
fig. 8. The electrodes are made of stout iron because a high thermal capacity is essential for the rapid extinction of the discharge. The recesses h contain

a mixture of substances from which alkali metals are liberated by chemical reaction, these metals coating the electrode surfaces. The reaction being progressive, this surface coating is regenerated during each discharge, to that it is always in a satisfactory condition, thus ensuring the requisite low dynamic breakdown voltage.

In the April, 1937, issue of Philips Technical Review, M. J. Druyvesteyn and the present author have discussed the general characteristics of discharges between parallel plane plates. The method of operation of the lighting arrester can be readily gathered from fig. 1 in that article, which has been reproduced as *fig. 9* here. In the present case, however, the voltage is drawn on a different scale, although the currents are approximately correct.

For the moment we shall neglect consideration of the delay in operation which in fact occurs only with an exceptionally steep voltage increase. It is apparent that the voltage must exceed a certain threshold value $B\ C$ for a fairly appreciable current

a



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b

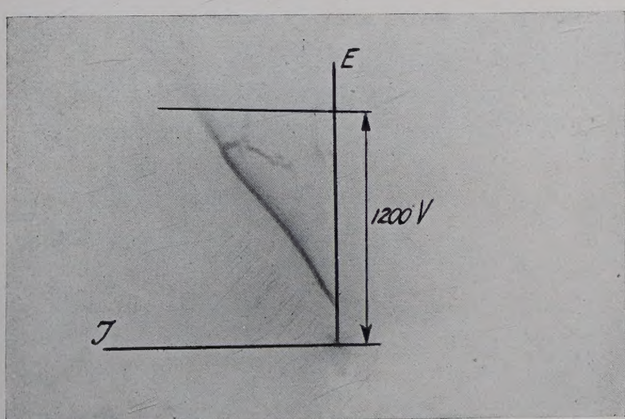

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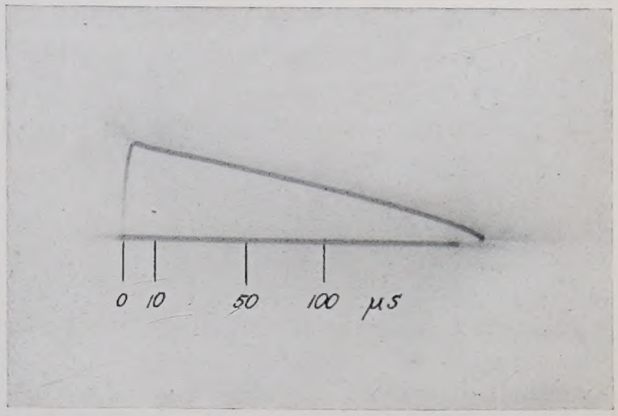
Fig. 10. a) Current-voltage characteristic of a Philips lightning arrester for low-tension networks, type 4394, when a positive current impulse of 300 amps with a wave front of 30 kilovolts per microsecond is applied.
b) The same for a negative current impulse of the same form and intensity.

[3]) Philips techn. Rev., **2**, 122, 1937.

to flow through the tube. Over the section $C\ D\ E\ F$ a corresponding current discharge takes place. The level of the threshold value $B\ C$ is determined



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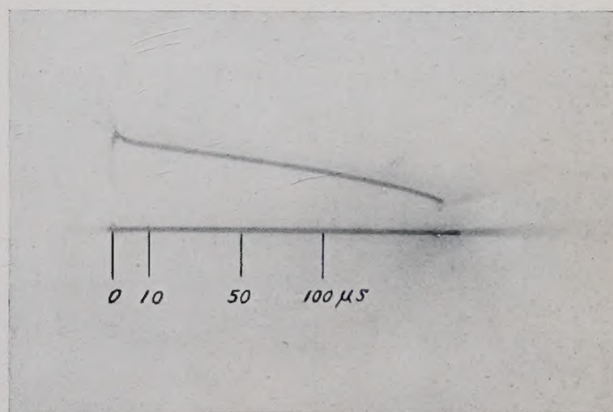
a



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b

Fig. 11a). Variation of current and b) variation of voltage plotted against the time when a discharge impulse of 300 amps is passed through a Philips lightning arrester, type 4394. The peak values of the current and voltage are 300 amps and 1320 volts respectively.

by the number of electrons which happen to be present in the gas. If no electrons are present, the threshold value is not reproducible; but the potassium coating on the electrodes (fig. 8) is slightly radioactive and thus furnishes sufficient initial electrons for the discharge to be always initiated at a specific voltage.

The shape of the section $F\ G$ in which the discharge is transformed to an arc is determined by the temperature of the electrode (cathode), which increases from F to G. To enable high current intensities to be dissipated, the threshold voltage F must be exceeded, this voltage being considerably higher than $B\ C$. But if the temperature of the electrode rises too rapidly after reaching the point F, the discharge voltage along the branch $F\ G$ may drop below the normal supply voltages. This signifies that after the surge disappears the arrester no longer has an extinguishing action, since the

extinction voltage is below the supply voltage. The arrester is then destroyed, for along the descending curve $F\,G$ the current can assume arbitrary high values until the material of the electrodes is fused.

But such a disastrously rapid increase in temperature is avoided by the high thermal capacity of the electrodes. Extinction is also promoted by the ease with which heat is conducted from the surface inwards as soon as the discharge current decays; the surface thus becomes rapidly cooled. It should be stated in this connection that with impulsive discharges the transient value of the current can be 1 000 to 100 000 times greater than shown in fig. 9 for raising the electrode to the requisite temperature, since this figure relates to a continuous static load.

The built-in series resistance R_v promotes regular extinction, for if the circuit has an adequate resistance a progressive increase of the current due to the mains voltage is prevented. But a resistance of this magnitude would make it impossible for the over-voltage impulse to assume considerably higher values than permissible with the steady current, as is in fact necessary. This difficulty may be overcome by making the resistance of a material whose specific resistance rises considerably with increase in voltage.

In this way, a rapid breakdown in the presence of an excess voltage as well as rapid extinction when the normal voltage is restored can be satisfactorily obtained.

In conclusion, reference must be made to some results of measurements made by the "Kema" on our behalf as regards the behaviour of the arrester with travelling waves. In these measurements, a voltage wave with a wave-front gradient of 30 kilovolts per micro-second and a duration of 100 micro-seconds was earthed through an arrester. The current-voltage characteristic was plotted for both polarities (*fig. 10, a* and *b*) for a current impulse of 300 amps; the variation of current and voltage are shown in the oscillograms reproduced in *fig. 11 a* and *b*. It may be concluded from these investigations that the lightning arrester operates so rapidly and at such a low voltage, and hence suppresses the voltage waves with such effectiveness, that it can with certainty prevent a breakdown of the insulation in electrical installations even when this insulation is of a low order.

MAGNET STEELS

by J. L. SNOEK.

Summary. The principal properties of a magnet steel are remanence and coercive force. How these properties are connected with the composition and the structure of the steel is discussed in this article on the basis of current theories of magnetism.

Introduction

Permanent magnets offer the important advantage, in comparison to electromagnets, that no supplementary source of energy is required for the purpose of maintaining the magnetic field. Where a constant magnetic field of given strength is required within a certain space, as in loudspeakers, gramophone pick-ups, ribbon microphones, small dynamos and measuring instruments, the permanent magnet is preferable to the electromagnet provided its use does not entail an increase in cost or weight.

Owing to the much improved magnetic properties of modern magnet steels, a very wide field has been opened up for the use of permanent magnets which in its turn has given the designer a variety of new problems to deal with. In this article, recent developments in the production of magnet steels will be discussed on the basis of current theories of magnetism.

Principles of Ferromagnetic Hysteresis

As a starting point, the hysteresis curve for an ordinary ferromagnetic material is shown in *fig. 1.*

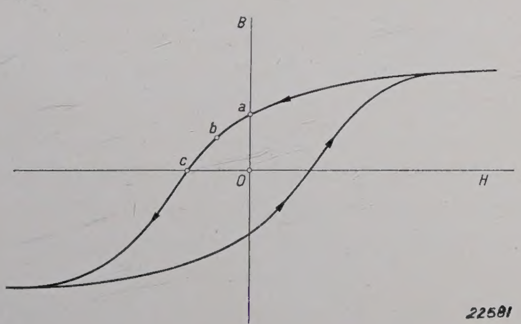


Fig. 1. Hysteresis curve *aO* is the remanence and *cO* is the coercive force.

The chief characteristic of this curve is that in strong magnetic fields the induced magnetism increases little, or not at all, with further increase in the field intensity, in other words with field intensities of the order of 1000 oersted a state of magnetic saturation is reached. The magnitude of this saturation is of interest in the course of our investigation, since as a rule the residual induction or remanence, which remains after the removal of the magnetic field, is roughly equal to half the magnetic saturation. If a high remanence is required, it is therefore important to use alloys having a high magnetic saturation.

If a magnetic field is applied in opposition to the direction of magnetisation and is steadily increased, the residual magnetism will become reduced as shown by the curve *a b c*, which has therefore been termed the "demagnetisation curve". The remanence eventually becomes zero at the point *c*. The field intensity applied when this point is reached is termed the coercivity or coercive force of the material and may be regarded as a measure of the hysteresis.

In determining the practical applications of a particular magnet steel, the remanence and the coercive force are not the only two properties which have to be taken into consideration, for the form of the demagnetisation curve is also an important factor. This curve must in fact be of such a shape that the product of the residual magnetism and the opposing demagnetising field can be made as large as possible. But since the shape of this curve, when reduced to equivalent values of the remanence and the coercive force, is roughly the same for all magnet steels, provided that flaws in casting and heterogenities in structure are avoided, it is apparent that the magnetic characteristics of a magnet steel are to a first approximation determined by the magnetic saturation and the coercive force. The various factors which influence these two magnitudes will be discussed individually below.

[1]) For further details of the many points raised in this article, reference should be made to the standard work of W. S. Messkin and A. Kussmann: Die ferromagnetischen Legierungen, (Berlin, 1932), which is cited as M.K. in the text.

[2]) In this respect, the magnetic steels are sharply differentiated from magnetically softer materials in which very considerable deviations may obtain. This marked difference may be accounted for theoretically by the very special character of the internal strains, as found for instance in a rolled nickel-iron strip (cf. Philips techn. Rev., **2**, 77, 1937), and the fact that these strains cannot occur in magnet steels in view of their treatment during manufacture.

Magnetic Saturation

At the beginning of this century the nature of the components of a material responsible for ferromagnetism was still very obscure. Nevertheless there was some justification for the assumption that in a magnetic substance the atoms themselves could be regarded as small elementary magnets. Ordinarily these small magnets have a random orientation owing to thermal rotational motions; but when an external magnetic field is applied to the substance they take up a definite configuration and assume a direction coinciding with that of the applied field, so that the magnetised condition becomes macroscopically apparent.

This theory provides a very satisfactory explanation of the behaviour of socalled paramagnetic materials, but on the other hand, it could not at the outset account for the behaviour of ferromagnetics, which differ from paramagnetics in that they can be magnetised with considerably lower field intensities and that after the removal of the field a certain residual magnetism remains.

Pierre Weiss was the first to point out that ferromagnetic phenomena could be explained on the hypothesis that a very powerful mutual action existed between the elementary magnets which tended to bring the latter into a mutually parallel configuration. According to Weiss the existence of this powerful intra-coupling of the elementary magnets was the sole difference between ferromagnetics and paramagnetics. These intra-molecular forces are so powerful that the material is always in a condition of spontaneous saturation. To account for the fact that a ferromagnetic can nevertheless be absolutely non-magnetic, Weiss assumed that the material was divided up into socalled elementary areas, within each of which the direction of the (spontaneous) magnetisation was entirely independent of that in any of the adjoining areas.

We now know that the carriers of the elementary magnetism of an atom are the electrons which are predestined for this duty by the nature of their linkage in the atom. The application of the modern electronic theory, particularly by Heisenberg and Bloch, has confirmed the basic assumptions of Weiss's theory and has enabled this theory to be further developed.

A theoretical explanation has indeed been forthcoming for the intramolecular forces demanded by the Weiss theory, but it appears that these forces are effective over very short distances only. The energy required to produce a marked deviation from parallelism is hence so great that large deviations between neighbouring particles will occur only rarely. Where the particles are separated by great distances, the coupling is in fact so weak as to be ineffective.

A weak magnetic field will suffice to produce a uniformly parallel configuration of the particles throughout a particular area, but thermal rotational motion remains a disturbing factor and its effect will be the greater the weaker the intramolecular forces [3]).

It is, in fact, possible to interpret quantitatively the variation of saturation with different series of alloys in terms of their composition by taking the above theory as a basis.

In general, the magnetic saturation of a series of solid solutions of two ferromagnetic elements varies, to a first approximation, linearly with the concentration. Where there is a marked deviation from this rule (cf. M.K., p. 125), these deviations may be explained by the forces operating between the elementary magnets being so weak at a certain concentration that thermal rotational motion assumes the upper hand. This is indicated by the marked depression of the Curie point.

Also in other cases, where heat treatment is found to have a marked effect on the magnetic saturation (nickel-manganese, cf. M.K. p. 134), the observed behaviour may be accounted for by deviations in the intramolecular forces as a result of a modification in the arrangement of the atoms.

On adding a non-magnetic material to an alloy the mutual forces are as a rule very rapidly reduced in magnitude.

In accord with these observations, the search for materials with a high saturation has been directed to the production of solid solutions composed of three ferromagnetic elements, viz., iron, cobalt and nickel, with small additions of other elements.

All alloys suitable for commercial uses are largely composed of these three elements, although very high coercive forces are also found with alloys containing little or even no iron alloys (e.g., the Heusler alloys, cf. M.K. pp. 146 - 146), but the remanence is so small that these alloys are of little practical use.

For the same reason, all other possible iron compounds, mainly mixtures of oxides isomorphous with magnetite (Fe_3O_4), are also unsuitable and valueless; these will therefore not be discussed in this article.

[3]) The intensity of this mutual action can be determined by measuring the critical temperature (the so-called Curie point), above which ferromagnetism disappears, giving place to ordinary paramagnetism.

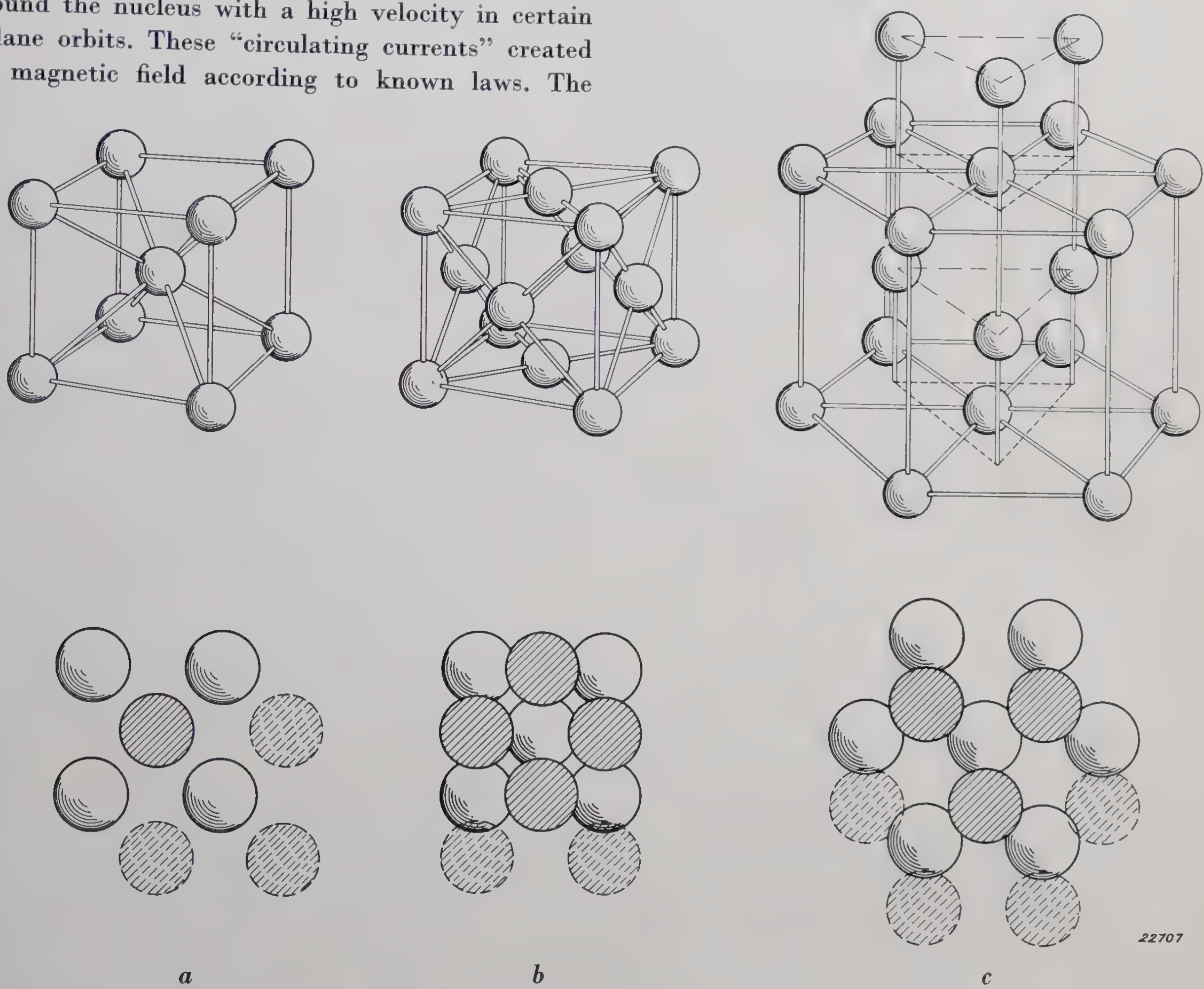
Coercive Force

To discuss the question of the coercive force of permanent magnets, the theory of magnetism must be considered in greater detail.

In the past an attempt was made to explain magnetism by assuming that the electrons circulated round the nucleus with a high velocity in certain plane orbits. These "circulating currents" created a magnetic field according to known laws. The main argument in favour of this hypothesis was that no other cause was conceivalble at the time. But from spectral investigations it appeared that each electron had its own magnetic moment, which gave rise to the conception that the electricity within the electron itself was circulating about a certain axis with a high velocity. From that time onward two possible causes for paramagnetism and ferromagnetism have thus been recognised.

Further investigations revealed that in nearly all cases the latter cause is alone responsible for the magnetic phenomena observed. The circulating currents compensate each other because just as many electrons spin in one direction as in the opposite direction. To a certain extent the same also applies to the magnetic moment of the electron itself, where again the axes of rotation of the different electrons are in the main opposed to one another. A small number of electrons (one or two per atom) is however not subject to this limitation in motion and it is just these electrons with their magnetic moments whose properties we have to consider.

The axial directions of the magnetic moments are on the whole easily rotatable, but in many cases this degree of freedom is restricted by a variety of factors.



Fiç. 2. Internal structure of the atom.
a) In a cubic space-centred lattice (alpha structure).
b) In a cubic body-centred lattice (gamma structure).
c) In a hexagonal lattice.
The diagrammatic plans below the structural models show the two lowest atomic layers (the second is hatched). The third layer then coincides with the first, the fourth with the second, and so on. The second atomic layer is shown shaded in order to indicate that it coincides with the first as regards the mutual arrangement of the atoms.

We have already stated that the small magnets composing a ferromagnetic substance are subject to mutual forces which tend to move neighbouring magnets parallel to each other. The common axis will then still remain freely rotatable, which is obviously not the case with a material having a coercive force, so that additionel forces have to be assumed to obtain a restricted rotation. These forces are provided by a mutual action between the electrons and the ionic lattice, which so to speak forms the framework on which the material is built up. As a result of this mutual action there are preferential directions in the crystal for the common axis of the specific moments to occupy, and a certain amount of energy, the socalled crystal energy, is necessary to rotate the magnetisation from a preferential direction into a less favourable one.

These forces cannot be calculated in advance, but it is evident from the above that their nature is closely dependent on the form of the ionic lattice. The three chief forms of lattice found in ferromagnetic metals are shown in *fig. 2*. With a lattice structure of pronounced asymetry, as shown in fig. 2*c*, the inherent moments exhibit a definite preferential direction. To serve as an example *fig. 3* shows the magnetisation curve of hexagonal

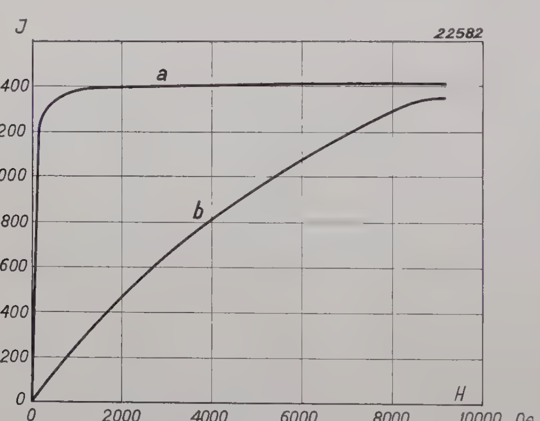


Fig. 3. Magnetisation curve of cobalt: a) in the direction of the hexagonal axis, b) in a direction perpendicular thereto. To obtain magnetic saturation in the second case a much higher field intensity is required than in the first case.

cobalt, curve *a* applying to magnetisation in the direction of the hexagonal axis and curve *b* to magnetisation in a direction perpendicular thereto. It is seen that the inherent moments tend to become parallel to the hexagonal axis, since a very high intensity is necessary to obtain magnetic saturation perpendicular to this axis. In cases where the symmetry is of a higher order, e.g. in cubic crystals, such as nickel and iron, the coupling is much looser; this follows from the fact that the three principal axes are equivalent from reasons of symmetry.

Now the majority of ferromagnetic alloys have a cubic symmetry, and in order to augment the linkage to the ionic lattice it is first necessary to reduce the high degree of symmetry obtaining. This can be done quite easily by applying a unilateral compressive or tensile stress to the material, when firmer bonds are produced almost exclusively, the existence of these bonds being exhibited by the fact that magnetisation is entirely different in the principal direction of deformation than perpendicular thereto.

Some materials, such as nickel, behave in the same way as cobalt when pressure is applied to them, viz., the inherent moments are located in preference parallel with the principal axis, while in others, such as iron, these moments are mainly perpendicular to the principal axis. When a tensile force is substituted for a compressive stress, the reverse behaviour is observed. It is thus possible to modify the positions of the elementary magnets relative to the ionic lattice and also their bonding forces by applying external forces.

Unfortunately, the existence of preferential directions of magnetisation is in itself insufficient for obtaining a high coercive force. The hysteresis loop of, for instance, a single crystal of cobalt is so small that it cannot be drawn in fig. 3. The same behaviour is observed with nickel under compression and iron under tension.

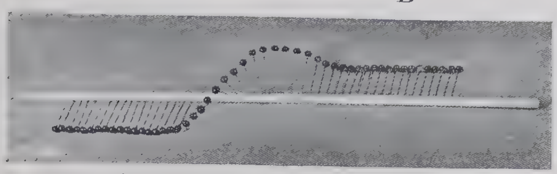
This failure is probably associated with the fact that a material, which is magnetised in a certain direction, always contains nuclei which are arranged in opposition to this direction. We will consider the effects of these nuclei using the model shown in *fig. 4*. Assume that the material has been magnetised principally in one direction A, as shown on the left of fig. 4, which at the same time is a preferential direction in the crystal. The part B shown on the right of the figure is a nucleus which has been magnetised in the opposite direction, this magnetisation being just as favourable as A in regard to the crystal energy. Between these two parts there will be a gradual transition, as indicated in *fig. 4*.

We thus see that in spite of the crystal energy no work is necessary to alter the state of magnetisation in the model shown in fig. 4; to effect this change it is only necessary to allow the nucleus B to grow at the expense of A. This will change the magnetic moments to the left of the transition zone from a favourable to an unfavourable configuration, while to the right of this zone exactly the same number of moments will be transformed from an unfavourable to a favourable arrangement.

In the case of a crystal lattice, the corresponding

conditions are rather more complicated than those shown in the model in fig. 4, and the coercive force will depend on the shape of the nuclei present. But

B



A

Fig. 4. This model shows how the magnetisation gradually changes between two areas with the elementary magnets in opposite configurations. By displacing the transition layer, magnetisation A (left) can be readily converted to magnetisation B (right).

again here the field intensity required to induce the growth of the nuclei will be smaller than is necessary in the absence of these nuclei for reversing the direction of magnetisation.

Hence, to produce a high coercive force, not only must magnetically-preferential directions be produced but the growth of nuclei must also be counteracted. Experiments have shown that this may result from marked changes in the direction and magnitude of the local strains.

These non-uniform strains always occur in commercially-produced materials owing to the presence of "disturbing" (i.e. insoluble) impurities, which also account for the fact that very low coercive forces were obtained in the case of iron only when this element could be prepared with a high degree of purity. On the other hand, soluble admixtures forming solid solutions with the iron have no effect on the coercive force, since very low coercive forces are found in the nickel-iron group of alloys. The following practical solution is thus arrived at for creating maximum strain abnormalities in iron by the intentional introduction of disturbing impurities: As much as possible of the foreign element must first be dissolved in the molten metal, so that by solution a uniform distribution of this element is obtained throughout the metal. During cooling segregation of the disturbing impurities occurs and the distribution of strain necessary in the alloy to obtain the requisite coercive force can be arrived at by regulating the conditions of cooling.

To illustrate how sharply the coercive force reacts to segregation, the results obtained in an investigation of rapidly-cooled mixtures of ferrosoferric oxide (Fe_3O_4) with mangano-manganic oxide (Mn_3O_4) are reproduced in *fig. 5*. It is seen that at a certain concentration limit the coercive force rises rapidly; at this point segregation evidently takes place during cooling.

Survey of Magnet Steels: The Oxide Magnet.

The oldest known permanent magnet, magnetic iron ore or loadstone, which is widely distributed

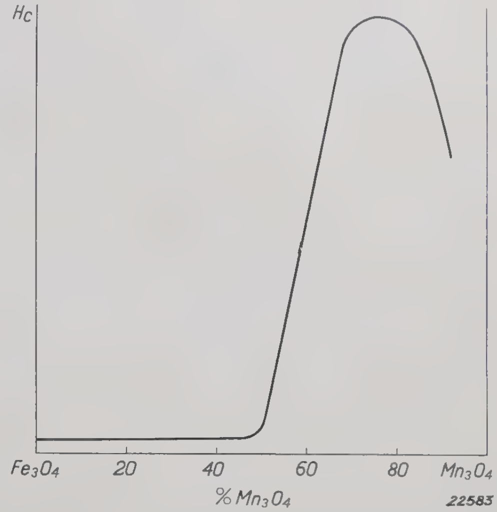


Fig. 5. Variation of the coercive force in rapidly- cooled mixtures of Fe_3O_4 and Mn_3O_4. At high temperatures, the formation of a solid solution is complete, but during cooling a slight segregation takes place which is distinctly revealed by the change in coercive force. Mn_3O_4 itself is non-magnetic.

in Nature, is the classic example of an oxide magnet of the type just referred to. The coercive force and particularly the remanence of this magnet are very unsatisfactory judged by present standards. During recent years the oxide magnet has been the subject of close research, and higher coercive forces have been obtained with it, although its low retentivity remains a serious disadvantage which has not yet been overcome.

Martensitic Steels

The first artificially-prepared permanent magnets used commercially were obtained by hardening steel. In addition to plain carbon steels, a distinction is drawn between chromium steels, tungsten steels and cobalt steels on the basis of the proportion of the predominating alloying element. A summary of the characteristics of these magnet steels, taking in each case the most reliable values, is given in the table at the end of this article. A marked preference is shown for cobalt steel, although the high price of cobalt prohibits its general use.

The hardening of steel does not exactly follow along the lines of the simple process described above. Yet the higher solubility of carbon, as the element responsible for the hardening of steel, at high temperatures than at low ones is used, although this increase in solubility is mainly due to the

[4]) J. L. Snoek, Physica, 3, 463, 1936.

iron having a crystal structure (austenitic or gamma structure) different at the high temperatures in question from that at low temperatures, when the structure is ferritic or of the alpha type (see fig. 2). With excess carbon and sufficiently rapid cooling, a transitional structure, martensite, is obtained which possesses a high mechanical and magnetic hardness. In modern steels, the use of carbon as an alloying element has been superseded, so that martensite is no longer an important component of magnet steels.

Non-Martensitic Steels

These steels may be classified in two groups. In the first group a metal, such as titanium, tungsten or molybdenum, is precipitated from the matrix as a compound, the best results being obtained with molybdenum dissolved in an iron-cobalt alloy. The description of the hardening process given above applies *in toto* to this type of alloy, and searching experiments have shown that here the increase in the coercive force takes place simultaneously with segregation, so that this segregation is fundamentally responsible for hardening.

In the second and technically more important group, the mechanism of the process follows along somewhat different lines. During segregation a compound is not directly precipitated from the matrix, which here has an alpha-structure, but an equilibrium is set up between the alpha phase referred to above and the gamma phase produced by cooling [5]). Owing to the marked difference in composition between these two phases, a separation of the homogeneous component in two phases is associated with an exchange of material between those regions in which the alpha phase persists and those where the gamma phase is produced. Segregation is therefore preceded by diffusion, during which a marked change in composition occurs locally in the metal before the formation of the gamma phase is initiated. This preparatory reaction, which is thus closely associated with the presence of a supersaturated solution, is the true cause responsible for magnetic hardening [6]).

It is probably not fortuitous that the best results have been obtained with just these steels, which include the Ni-Al and Ni-Al-Co-Ti alloys. As already indicated above, the maximum attainable deformation of the metal should be produced; during this transformation the limit of elasticity of the material is usually reached. If a crude process is employed resulting in the appearance of discontinuous transition phases, the mutual bonds between the particles will be disturbed so that the original structure will be partially reconstituted. In fact, it has been observed during transformation from the alpha to the gamma phase that in a certain transition state the metal is mechanically very weak. This is in complete agreement with the observation that in the case of Fe-Ni-Al steel this transformation is not initiated at the same time as the coercive force increases, but that on the contrary the transformation is a sign of an almost abrupt decrease which is probably connected with a partial "slipping" of the material. On the other hand, during diffusion preceding slipping the strains are to a certain extent built up step by step, so that cohesion between the atoms is never for a moment lost.

The table below correlates the magnetic properties of the principal magnet steels.

Table I.

Material	Remanence in gauss	Coercivity in oersted
Carbon steel (plain)	9 000 - 8 000	50 - 60
Tungsten steel	12 000 - 11 000	56 - 67
Chromium steel	10 800 - 9 700	58 - 66
Chrome-tungsten steel . . .	11 000	76
Cobaltsteel	9 000	300
Ni-Al steel	6 000 - 5 000	400 - 600
Ni-Al-Co-Ti steel	8 000 - 6 000	600 - 900

[5]) W. G. Burgers and J. L. Snoek, Physica, **2**, 1063, 1935.

[6]) The same has been found for duralumin which was hardened in the same way.

TECHNICAL CONSIDERATIONS IN THE LIGHTING OF COUNTRY ROADS

by G. B. VAN DE WERFHORST.

Summary. In this article the standards underlying the assessment of lighting conditions on highways are discussed. Originally the intensity of illumination measured horizontally was taken as a criterion for this purpose; later the brightness of the road surface was favoured, while at the present time the contrast between the object and the background is taken as a standard of comparison. The coefficients of reflection of the object and the background, the comparative values of specular or regular reflection of the road surface, the screening of the emitted beam which is necessary to avoid dazzle, as well as the effect of the area of the radiating surface of lamps, are also discussed.

In this article road or highway lighting embraces the illumination of highways and roads situated outside built-up areas. The principles which underlie the planning of a new lighting installation and which have to be considered in assessing the efficiency of existing installations have already been discussed in a previous article [1]). The subject matter of that article may be briefly summarised as follows: Fixed lights which are provided in the public interest on all class I country roads and on certain class II roads must afford such conditions of visibility that the traffic on these roads can circulate with all reasonable safety.

A speed of 50 m.p.h. should be reasonable and permissible under the conditions of illumination provided. Aesthetic considerations regarding the colour of the light do not come into question; disturbing effects originating from light sources outside the road boundaries must be eliminated.

The driver of a car must be able to perceive immediately the presence of any obstacle situated at a distance exceeding 300 yards. Moreover within this distance, it must also be possible for him to recognise the exact nature of the object. At the same time objects within this distance and approaching from a lateral direction must produce such a peripheral stimulus that the driver is able to react directly to this stimulus. The speed with which an object can be perceived and recognised is thus of paramount importance in the present case. Supplementary lighting of the edges of the road and of strips skirting it is essential for satisfactory perception.

Far removed from the application of the above basic principles, it was believed a few years ago that the lighting of a highway could be assessed exclusively from the amount of light incident on the road surface in a horizontal direction (the horizontal intensity of illumination in lux). It is evident that this gave a one-sided and erronous scale of measurement, since we are never able to see directly the light falling on a surface or on a solid object, but only that part of the incident light which is reflected by the surface in the direction of vision. We see the brightness of the illuminated surface in the direction of vision and not the actual intensity of illumination. In recent years, closer attention has therefore been given to the brightness of road surfaces and various attempts were made to increase it. Cohu [2]) has investigated the reflection properties of road surfaces in order to determine from the intensity of illumination the brightness apparent to the road user. Paterson, Waldram [3]) and others have studied means for increasing the brightness of road surfaces and methods for measuring the brightness values. Yet the conditions of perception required to make traffic safer are not determined merely by the brightness of a highway, for perception demands the existence of a contrast, and in fact a contrast between the object viewed and its background. In the present article, the contrast is defined as the ratio of two brightnesses, of which one, e.g. that of the road surface, is greater than the other, viz., that of the object. In regard to our perceptive abilities, this ratio is not of the nature of a constant, since the contrast sensitivity of the eye is not the same at all brightness levels. The contrast sensitivity becomes reduced with diminution in brightness, and at low brightness levels only comparatively heavy contrasts can be differentiated [4]). Since from considerations of cost, it is necessary to make do with low intensities of illumination for lighting country roads, we are compelled to take into account the lower contrast

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[1]) Philips techn. Rev., **2**, 110, 1937.

[2]) M. Cohu. Revue génerale de l'électricité, **37**, 755 - 767, 1935.

[3]) C. C. Paterson, Modern Street Lighting, J. Record Trans. **45**, part 4, 1935, J. M. Waldram, Road Surface Reflection, Ill. Eng., **27**, 305 - 313 and 339 - 351, 1934; **28**, 34, 1935.

[4]) Cf. also P. J. Bouma, Philips techn. Rev., **1**, 166, 1936

sensitivity of the eye at these brightness levels. We must therefore make the fullest use of all properties of the highway and of the objects on it in so far as they affect the conditions of reflection, so as to arrive at the maximum possible effect [5]). The already low contrast sensitivity of the eye must also be prevented from becoming further reduced by the presence of disturbing influences, such as dazzling light sources.

Owing to the diversity of conditions arising, it is only possible to discuss in broad outline the reflection characteristics of a highway, including the kerbs and pathways skirting it, and those of the objects on the roadway.

It should be noted at the outset of this discussion, that an illuminated surface or object never reflects all the light incident on it; a greater or lesser fraction of this light is always absorbed, while the reflected component can be reflected in a variety of ways. To understand exactly what occurs, we must examine in closer detail the nature of reflection.

A distinction is drawn between diffuse and regular or specular reflection. A surface with diffuse reflection reflects the incident light uniformly in all directions irrespective of the angle of incidence of the light, so that the surface appears equally bright when viewed from any direction, e.g. a matt stucco ceiling, a sheet of matt white drawing paper or of grey drawing paper, which however reflects a much smaller part of the incident light. The apparent brightness of a surface with diffuse reflection depends, *inter alia*, on the quantity of light incident on it and hence on the distance between the light source and the illuminated surface; the brightness of the surface is always much lower than that of the light source.

On the other hand, a surface with regular-reflecting properties reflects the incident light in one direction only as determined by the direction of incidence of this light. On looking at the surface in a direction coinciding with that of the reflected light rays, the image of the light source is seen. Since with a "mirror" of this type the absorption loss is small, the brightness of the image is roughly equal to that of the light source itself, and in fact quite independent of the distance between the light source and the illuminated surface. But if the surface is regarded in a direction other than in that in which the light is reflected, it will appear dark, irrespective of the amount of light falling on it. Examples of this ordinary mirrors and smooth surfaces of water.

Perfect diffuse and perfect regular reflection are extreme concepts, which are obviously opposites in almost every particular. The mistake is frequently made in practice of taking one or other of these extremes as the only standard; objects and surfaces which conform wholly or almost wholly to one or other of these extremes of reflection are exceptions. Very frequently diffuse and regular reflection occur simultaneously, and often one or other predominates. Thus for instance ordinary glazed paper has mainly diffuse reflection, although the smooth surface also produces a secondary regular reflection. A mirror with a thin film of dust exhibits principally regular reflection, although the dust particles on the surface also give diffuse reflection.

In such cases the reflecting surface may be roughly regarded as homogeneous in so far as reflection is concerned. On the other hand, there are many practical cases which are not homogeneous of which some give diffuse reflection, others regular reflection and still others both types of reflection. This heterogeneity of reflection is found, for instance, with a host of small mica chips and in fact in all kinds of crystalline formations in natural rocks. Every stone pavement and many tarmacadam road surfaces exhibit this combination of reflections. A section through a road surface of this type is shown in *fig. 1*, where the surfaces A_d and B_s

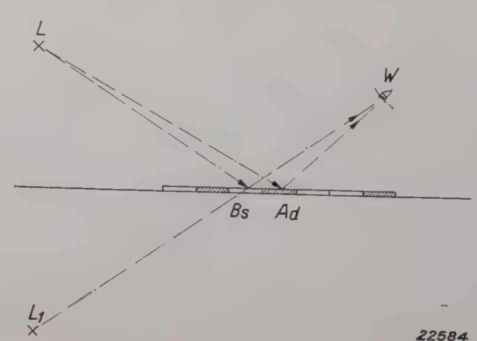


Fig. 1. Road surface with areas of regular reflection (B_s) and of diffuse reflection (A_d).

reflect the light rays emanating from a light source L by diffuse and regular reflection respectively. The observer W views the surface A_d with a certain brightness at a distance WA_d, while in surface B_s he sees the light source L specularly reflected at L_1 and at a distance WL_1. Hence, the observer when looking at a point on the road surface must accommodate his eye to two very different distances, which is naturally very difficult. Without being conscious of this fact, the observer may frequently

[5]) Where contrast is referred to in this article, only one type of contrast is implied, as for instance that obtained by illumination with socalled "white light" (light sources with a continuous spectrum: sun, gaslight, incandescent lamps, etc.).

find it difficult to judge the distance of a certain point under these conditions, since he cannot see the exact position of the point distinctly [6]).

Not only must the regular-reflecting parts of the road surface be taken into account in this connection, but it has to be remembered that many areas giving diffuse reflection when dry become converted to areas of regular reflection in wet weather. A road surface which in dry weather is almost wholly diffuse-reflecting may exhibit a combination of both types of reflection when wet, e.g. brick paving. In fact in wet weather regular reflection may predominate.

In the cases discussed here, it has always been assumed that a given reflection can be resolved into two components, of which one may be regarded as regular reflection and the other as diffuse reflection. In very many cases, this resolution is however not possible, and reflection is more of an intermediate nature which cannot be resolved as a combination of diffuse and regular reflection, but requires for description a notation of its own which is still lacking. Hence, in analysing road lighting conditions, we are compelled to make do with the terms "diffuse reflection" and "regular reflection", and later when discussing the conclusions arrived at we can speculate on the possible significance attaching to the occurence of an intermediate form of reflection of the type referred to.

After this digression we can return to a consideration of the road and of the objects present on it. The objects on a highway may be divided into two main groups: Individuals and vehicles. Individuals include pedestrians, cyclists and motor-cyclists. With all individuals, including motor-cyclists, the reflection properties of their clothes are the determining characteristics, and by a sheer accident introduce no difficulty in dealing with this problem. We can in fact start from the assumption that clothing is always diffuse-reflecting. Bouma carried out measurements of the different coefficients of reflection and examined the frequency of their occurrence. His results are correlated in the form of curves in *fig. 2*. It is seen that in most cases the coefficient of reflection of overcoats is below 1 per cent and of other garments below 2 per cent, and that coefficients of 6 per cent occur only rarely. If we therefore take a mean coefficient of 5 per cent for individuals, we are erring on the right side.

In the second group comprising vehicles, practically only power-driven vehicles, some with trailers, have to be considered in the case of country roads under discussion here. A recent census showed that 80 per cent of these vehicles are dark in colour

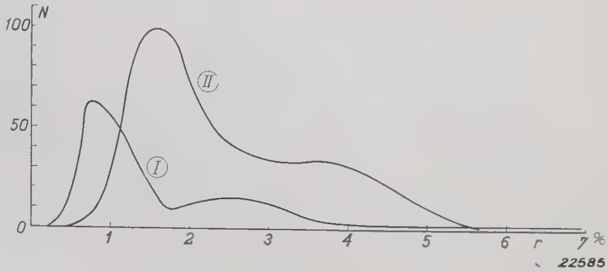


Fig. 2. Coefficients of reflection of clothing. Curve *I*: Overcoats, and curve *II*: Other outer garments. The coefficient of reflection r is plotted in percentages along the abscissa, and the frequency with which a garment of a given coefficient of reflection occurs relative to another is plotted along the ordinate.

2 per cent very bright, while the colour of the remaining 18 per cent conforms roughly to the average hue of the road surface. To investigate how sharply these vehicles stand out against the background, we will neglect the regular reflection of the vehicles, since it is only important when the light of a street lamp incident on the vehicle is reflected directly in the direction of the eye of a person on the road; it is obvious that this will only result in an accidental flash of light being received. The liability of regular reflected light rays of this type falling on the eye of a person on the road may be augmented by the three following circumstances:

a) Most private motor cars have curved surfaces of a variety of shapes: The different areas on a vehicle of this type will therefore reflect the incident rays in many directions. On the other hand, most commercial vehicles have few specularly-reflecting surfaces and parts, while their contours are also much flatter. The liability of fortuitous flashes in the direction of another road user is hence very small with these vehicles.
b) As a rule the person on the road is himself moving and is continually changing his position with reference to the vehicle seen under the light of a lamp; if the vehicle gives any regular reflection a reflected light ray will then strike his eye for a brief period in each direction of regular reflection.
c) The vehicle seen under the light of a lamp is itself moving. In this case, in conjunction with the conditions referred to under b), the danger of a road user receiving an accidental flash will be much increased. If, on the other hand, the vehicle is stationary, this liability is limited to the two cases a) and b), which must obviously

[6]) As long as his field of vision contains a sufficient number of well-defined and recognisable characteristics, the observer on the road will hardly be aware of this lack of visibility, particularly as he does not focus the eye on to the road surface. But if the conditions on the road surface closely approach those under consideration here, which may occur on a wet road during the evening, the surface will appear blurred to the road user and will not exhibit sufficient characteristics.

not be over-estimated in the case of non-specularly-reflecting vehicles, such as the majority of commercial vehicles. For this reason stationary vehicles are very dangerous. If the background and the object appear to the road user to have the same brightness and no difference in colour (which is in fact more frequently the case with existing road-lighting systems than generally assumed, the road user will barely be able to perceive the object owing to the absence of a contrast. Moreover, the motion of an object contributes considerably to visibility.

However the problem is regarded, the feasibility of perception, which in fact demands something more than that light rays shall accidentally impinge on the eye for a very brief period, remains an uncertain factor which is incapable of calculation. Regular reflection of the vehicles must therefore not be taken as a basis in planning a lighting installation, and it should be regarded merely as a contribution to the general effect produced by the lighting. In regard to the diffuse reflection of vehicles, a coefficient of reflection not exceeding 5 per cent applies for vehicles with a dark finish, and one of 50 per cent for the very small group of vehicles with a very bright finish. For the intermediate group, which as regards brightness and colour is comparable to an average road surface, the accidental flashing of reflected light rays already referred to must provide us with a means of safety.

Considering vehicles and individuals in a single group, a coefficient of reflection of a maximum of 5 per cent can be taken as a reasonably accurate basis.

The reflection of the road surface is less uniform: Stone pavements (many types of stone), brick paving, asphalt surfaces (in great variety) and concrete surfacings exhibit considerable differences. Moreover, many road surfaces have an intermediate form of reflection as referred to above. It is, therefore, practically impossible to ascribe specific coefficients of reflection to a road surface, which can be taken as a reliable basis for calculations.

In contradistinction to these indefinite factors, we have however the following well-defined criteria:

Assume that we are standing during the day on a long straight country road, whose right-hand traffic lane has a surface of grey asphalt, while the left hand lane (a subsequent widening of the original road) has a greyish-yellow asphalt surface (rolled gravel); along one side the road is skirted by a pavement of Swedish granite and along the other side by brick pavement.

On looking at the different road surfaces, a definite brightness stimulus is obtained from each half of the road. The greyish-yellow asphalt appears brighter than the grey, and the Swedish granite pavement brighter than the greyish-yellow asphalt. A marked difference is moreover apparent between the brightnesses of the Swedish granite and brick pavements. Each part of the road surface gives its own general brightness stimulus and these stimuli merge to a uniform brightness only at a point miles along the road. The brightness stimuli from the different road surfaces are so characteristic, both when viewed against each other and individually, that it must be found possible to express these differences in terms of specific coefficients of reflection (cf. fig. 3).

Fig. 3. Example showing the importance of illuminating the areas skirting country roads in addition to the road itself, so as to obtain a sufficiently extensive background. It may be seen how each of the traffic lanes produces its own particular brightness stimulus.

We might be inclined to regard these pronounced differences to be due to colour stimuli. But if we look at the same road under monochromatic light from sodium lamps the same stimuli are experienced, so that the observed differences must be considered as due to differences in brightness.

If, now, we take a series of samples of diffuse-reflecting paper with different tones of grey, whose coefficients of reflection have been determined by careful calibration and which differ by only 2 per cent from each other, and place these samples on the different parts of the road referred to above, we can determine by direct observation which sample on each part of the road has the same brightness as the road surface itself, and cannot then be readily distinguished. It is also possible to determine which samples are brighter and which darker than the surface; this can be done so accurately that the

coefficient of reflection can be precisely determined to within 1 per cent.

We can thus express the above-mentioned pronounced total brightness stimuli in terms of a moment consider only diffuse reflection (regarding regular reflection, see below), it is evident that under an equivalent illumination an object with a coefficient of reflection below 5 per cent will appear

Fig. 4. The object on the roadway stands out dark against the bright background.

Fig. 5. In daylight also, the object appears dark against the background, except the ladies with very bright summer dresses cycling along the side track.

coefficient of diffuse reflection of these samples. In this way we can deduce that the coefficients of reflection of the different parts of the road lie between 5 and 35 per cent, except for isolated areas of (black) tarred asphalt. If, furthermore, we assume a value of 10 per cent for the average road surface, pathways and skirting fields, and for the dark against the brighter background. This result, which may be frequently observed in daylight (cf. *figs. 4* and *5*), must therefore be utilised to the full when artificial illumination is provided [7]). To

[7]) It may be noted in this connection how few colour contrasts, even during the day, play a part in the perception of objects on the road.

the road user, the road and its boundaries appear as horizontal surfaces and the object mainly as a projection on a vertical plane. To obtain the greatest contrast it would, therefore, be ideal to make the bright horizontal surface as bright as possible and in particular leave the dark, vertical surfaces as dark as possible; this would require a system of illumination which throws the whole of its light vertically downward. An ideal system of this character cannot be realised in practice, and we are compelled to adopt a compromise in the form of a number of separate lighting units located at definite distances apart and mounted at a certain height, and at the same time cut out all non-vertical rays. Various problems have then to be considered, such as the best type of lighting unit, the optimum distances apart and the most suitable mounting heights, as well as the most favourable distribution of light from the lamps. If both the object and the road surface may be assumed to give only diffuse reflection, the optimum characteristics could be determined to a fair degree of accuracy by taking as a basis the coefficients referred to above. The brightnesses are then proportional to the illumination intensities and could be deduced directly from the latter. While diffuse reflection alone comes into consideration with objects on the road, regular reflection also must be taken into account when analysing the conditions of illumination on the road surface. As already stated above, different road surfaces have very different regular-reflection values which moreover vary with the angle with which the road user views the road surface and with the angle of incidence of the light [8]). Since, as already pointed out, the light from the lamps is not radiated exclusively in a vertical direction and all possible angles of incidence below 90 deg. have therefore to be taken into account, calculation is rendered very difficult by these highly variable factors which are moreover by no means easy to assess quantitatively. Laboratory measurements with small samples of road surface materials may give very interesting data for the theoretical assessment of the brightness stimuli, but the surface of an open road will be found to give entirely different brightness values. The reason for this is that, in the first place, our perceptions produce a total stimulus which is by no means equal to the sum of the component stimuli as determined in laboratory tests. Moreover, in practice the brightness stimulus is affected by the colour of the light and the more or less marked dazzle due to roadside and vehicle lamps. If all these influences could be taken into consideration when planning a lighting scheme, it would still be impossible to assess what effect each of these factors has on the visibility on the highway in the case of an existing installation. A most important advance in dealing with this problem has therefore been made with the appearance of the Philips visibility meter which was evolved by Holst and Bouma and provides means for the direct measurement of the visibility on the road itself together with all associated effects [9]). From a large number of measurements made with this visibility meter on various highways a minimum visibility value for the contrast on the road has been found which must be satisfied by the conditions of lighting to permit traffic to travel with reasonable safety at a speed of 50 m.p.h. It has been shown that to achieve this end the object and background must have an average minimum contrast of 3 : 4 [10]).

It has been frequently recommended that the best way to improve the contrast is to make use of the regular reflection of the road surface. Since the regular reflection of every surface increases the smaller the angle of incidence of the light rays, it has been assumed that this property could be used with advantage in road lighting and the light distributed with very low angles of incidence. Moreover it is claimed that this also has the advantage of permitting the lamps to be placed at greater distances apart and at lower mounting heights. The nature of this problem is illustrated in greater detail in *figs. 6* to *9*, where AB is a much magnified part of the road surface as seen by the road user W between the points A and B. This surface is illuminated by rays from the light source L impinging in the direction *1*. Since the surface AB is assumed to be very small, the incident rays may be regarded as forming a parallel beam. In all figures only that part of the light subject to regular reflection is shown. In *fig. 6* the incident rays make an angle α with the horizontal; part of these rays, viz., *1*, *2*, *3*, *4*, *5*, *6*, strike the surface at points where they are reflected in the direction of vision of the observer. On the other hand, rays *7*, *8* and *9* are, for example, reflected in such directions that they do not reach

[8]) The angle of incidence is here defined as the angle which the incident ray of light makes with the horizontal road surface, and not as the angle between the ray and the perpendicular drawn to this surface.

[9]) Cf. Philips techn. Rev., **1**, 349, 1936.

[10]) Actually, we have here introduced a new basis for the assessment of the quality of a lighting system, viz., „the feasibility of travelling with safety at a speed of 50 m.p.h."

the observer and thus do not contribute to this brightness stimulus. Other rays again, e.g. *10* and *11*, although reflected in the direction of the observer are prevented from reaching him by inequalities of the at all is reflected in the direction of the observer. who thus sees *AD* as a dark patch.

In wet weather, the depressions in the road surface are filled with small puddles, as shown in

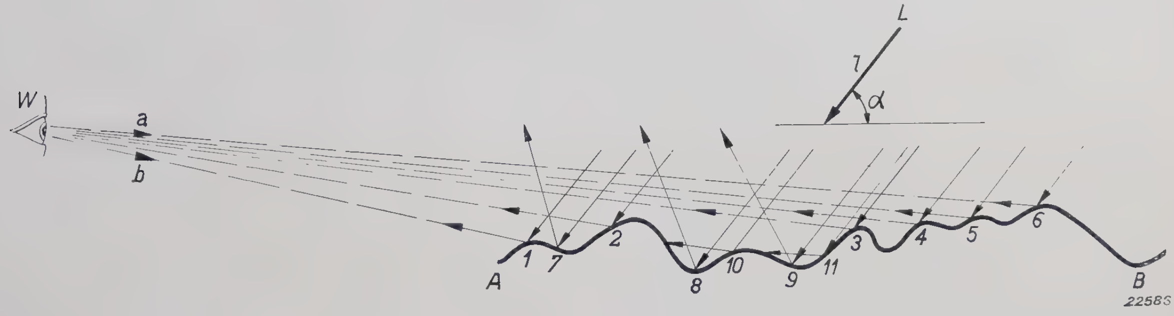


Fig. 6. Regular reflection at a highly-magnified area of a road illuminated at an angle α; part of the light is reflected towards the observer and part in an entirely different direction, while still another part is absorbed by inequalities on the surface.

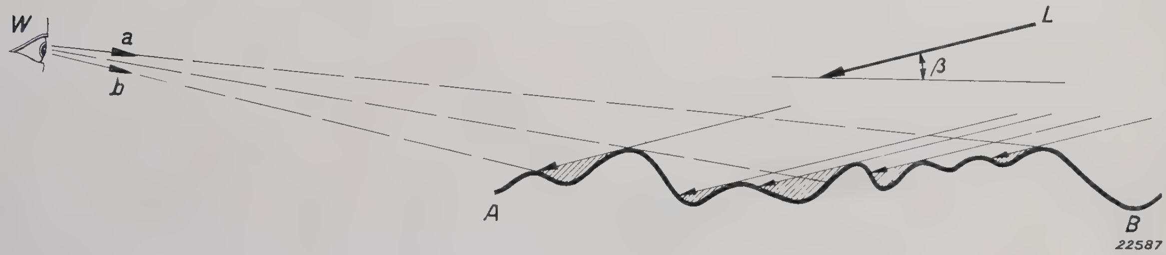


Fig. 7. Regular reflection at a highly-magnified area of a road surface illuminated at an angle β, with the inequalities of the surface casting shadows.

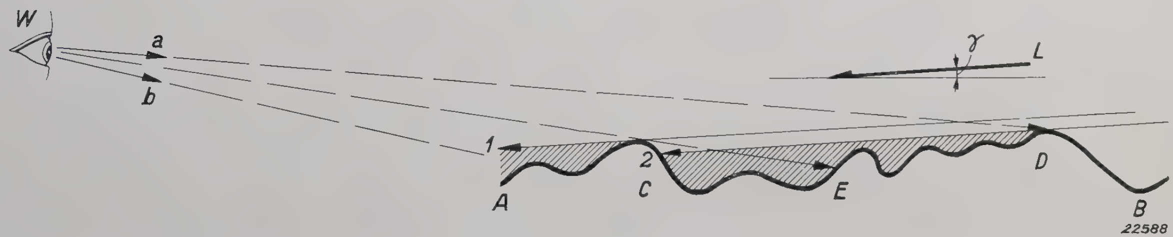


Fig. 8. Regular reflection at a highly-magnified area of a road surface illuminated at an angle γ. The surface inequalities cast long shadows; the areas in shadow also cannot give diffuse reflection.

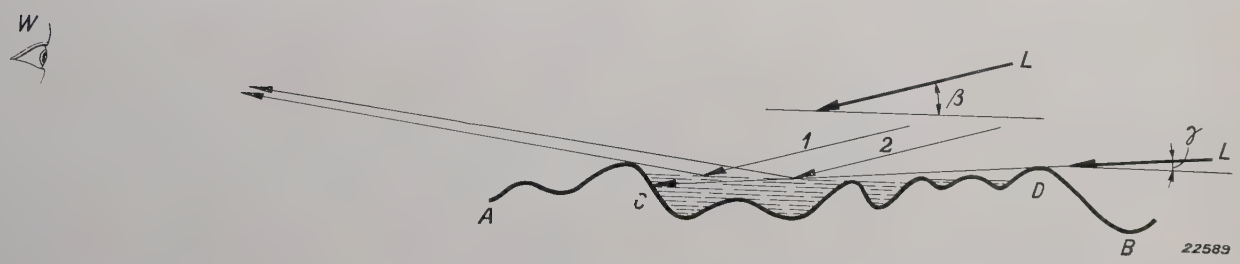


Fig. 9. Regular reflection at a highly-magnified area of a road surface in wet weather when illuminated at an angle β or γ; with an angle of incidence of γ the effect of the long shadows on the whole persists.

road surface. If a surface with similar contours is illuminated at an angle β as shown in *fig. 7*, the observer already sees fairly large areas of deep shadow on the road. If the angle of incidence is still further reduced, to γ as in *fig. 8*, the area from *A* to *D* remains in deep shadow, so that no light *fig. 9*. With an angle of incidence of β regular reflection may indeed be greater in the direction *W* than shown in fig. 7, although with an angle of incidence of γ the area *CD* remains in shadow and only the regular reflection occurring at the highset points of the surface is visible.

Fig. 10. With a very acute angle of incidence, only the highest points of the wet surface reflect the light specularly.

It must be remembered that even the smoothest road never has a mathematically smooth surface, particularly as it is frequently made rough to prevent skidding. Experiments have shown how with small angles of incidence inequalities of the order of a few millimetres appear to the observer to be depressions several centimetres deep. Owing to the presence of long shadows, there is just as little likelihood of diffuse reflection with small angles of incidence, since the areas CD even if giving perfect diffuse reflection receive no light at all and cannot therefore give a reflection. A depression of 9 mm will in fact give a shadow 10 cm in length with an angle of incidence of 5 deg. The moderate degree of reflection obtained with these angles of incidence is apparent if we consider the inequalities due to ruts in asphalt road surfaces carrying a heavy traffic. Only the peaks give regular reflection along the line joining the observer and the light source; beyond this line everything appears dark to the observer and narrow streaks of light are in consequence produced on the dark road surface (cf. *fig. 10*). In practice it is useless to attempt to increase the brightness of the road surface by using angles of incidence less than about 10 deg., in other words to use that part of the rays emanating from the light source L which make an angle β with the area AB (see *fig. 11*). There is, however, another reason which is a serious obstacle to this kind of illumination. Assume that in fig. 11 W_1, W_2, W_3, W_4 are points on the level of the eye of a road user moving in a forward direction. If the light source L emits rays in the whole of the region below the horizontal, light rays will fall on the observer's eye to the left of W_2 when these make angles of less than 10 deg. with his direction of vision assumed to be straight ahead horizontally, and to the left of W_0 when these angles are smaller than 15 deg. Nevertheless, it is found that dazzle, i.e. the reduction in the contrast sensitivity, is a maximum when the angle of incidence of the light rays on the eye is small [11]). Thus Bouma, among others, found that with white light impinging at $\beta = 2.5$ deg. and under conditions normally occurring on a roadway the contrast sensitivity is reduced to 43 per cent of the value obtained in the absence of dazzle, and at $\beta = 5$ deg. to 62 per cent [12]). Bouma and other investigators [13]) observed that the contrast sensitivity is reduced to the minimum permissible values only when the angle of incidence exceeds 15 deg. (Bouma considers 15 to 20 deg. as desirable). Direct rays from the light source L must not impinge on the eye before the observer reaches the point W_3, so that all light beyond this angle of $\beta = 15$ deg. must be screened off.

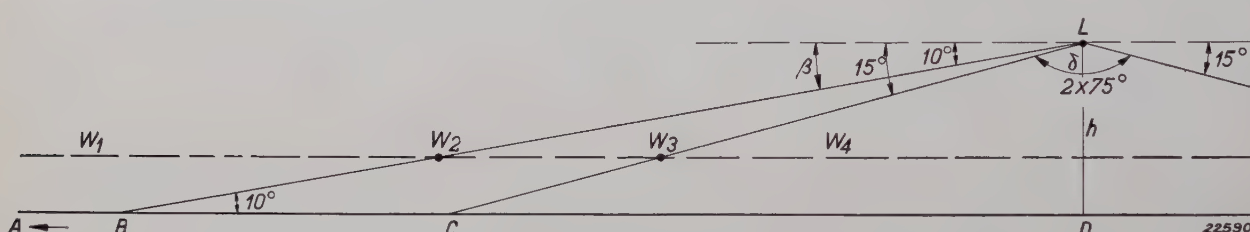


Fig. 11. Vertical section through a road, illuminated by the light source L, and with a moving observer W whose eye travels along the line W_1 W_2 W_3 W_4. The light radiated from L is screened to form a beam with an angle δ (2×75 deg.).

The permissible angle of radiation δ of the lamp must therefore be: $\delta = 2 \times 75$ deg.; for a given mounting height h of the lamp, this angle determines the range and hence also the interval a

[11]) The angle of incidence is here the angle which the light rays make with the direction of vision of the observer.

[12]) P. J. Bouma, De Ingenieur, **49 A**, 290 - 294, 1934.

[13]) Philips techn. Rev., **1**, 225, 1936, and the references given in that article.

between lamps; conversely with a given interval a between the lamps the mounting height h is fixed. It now only remains to determine the distribution of light from the lamps with particular light sources.

Within the angle of radiation of the lamps found above, regular reflection of the road surface, particularly in wet weather and with most surface materials, may become an important consideration. Taking this type of reflection as a basis, definite specifications for the design of the lamps and the characteristics of the light sources can be deduced. In *fig. 12* the conditions of illumination on a road

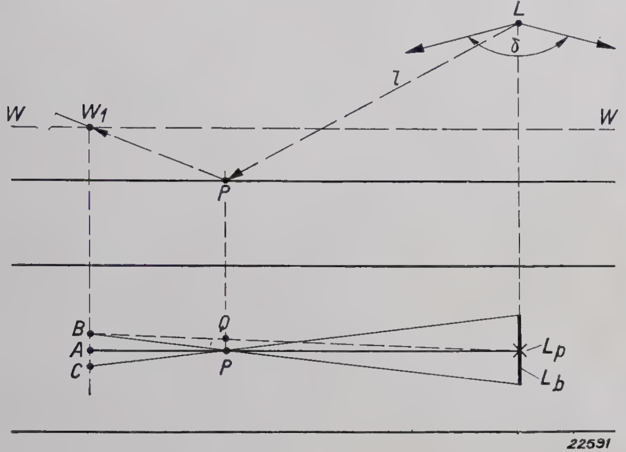


Fig. 12. Plan and elevation of a road illuminated from a light source L above it, showing the effect of regular reflection on the observer W, with a punctiform source L_p and with a transverse source L_b.

illuminated by the light source L and with the observer's eye at a level WW are shown in plan and elevation (for the sake of simplicity the beam of light and the direction of vision of the observer are assumed to be straight along the road). First, regard the light source L as punctiform L_p, e.g. an electric lamp with a clear bulb or a lamp with prismatic glass so that the lamp appears to radiate light in all directions as a point source. The observer at A sees the point P of the road surface illuminated with a brightness of the same order as that of the light source (regular reflection alone is being considered here). If the observer is at B, he will see the point Q similarly illuminated, while the point P will appear dark. If we now take a light source L_b giving the same luminous flux, but with a larger radiating surface in a direction transverse to the road, the observer will then see the point P on the road surface brightly illuminated not only from his position A but also to the side of A as far as B and C. It will always appear with a lower brightness than in the former case, since the light source L_b owing to its greater radiating surface will have a lower brightness than the light source L_p assuming the total luminosities are equivalent. By using a light source L_b placed perpendicular to the length of the road, regular reflection may be obtained also at inequalities of the road surface, embracing the above-mentioned areas reflecting in all directions, such reflection being apparent no

Fig. 13. Transverse light sources with large radiating surfaces produce wide luminous bands with a comparatively low brightness on a wet road surface.

longer as narrow bands of dazzling brightness, but as broad bands of lower brightness (see *fig. 13*), so that the troublesome dazzling reflection obtained with a punctiform light source L is avoided. Furthermore, by a judicious arrangement of light sources, these wide luminous bands may be brought contiguous to each other so that also in wet weather the road surface appears bright overall.

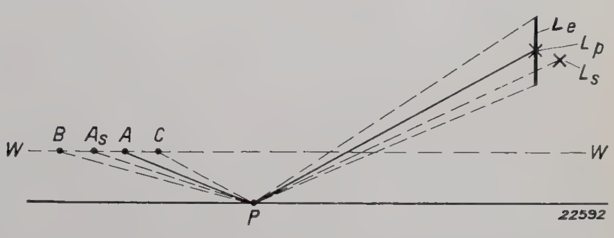


Fig. 14. Vertical plane to a road with an elevated light source L, showing the effect of regular reflection on an observer W with the eye at a level WW, with a punctiform light source L_p, with a vertically-expanded light source L_e and with a specular reflector $L_p + L_s$.

A similar effect is produced when the light source is expanded in a vertical direction. It may be seen from *fig. 14* that with a punctiform source of light L_p illuminating a horizontal specularly-reflecting

part of the road surface, the observer sees the point P brightly illuminated only from A. But if the lamp is given a greater radiating surface in a vertical direction, e.g. equal to the apparent surface of an enamelled reflector, so that it acts as a light source L_e, the observer will see the point P brightly illuminated on moving from B to C, and with a lower brightness exactly as in the previous case. If the enamelled reflector is replaced by a specular reflector, the latter will give a mirror image for each point, e.g. L_s for the point P. The observer will then however see the point P illuminated not only at A, but also at A_s, although again with a much higher, usually dazzling, brightness; moreover the distance from which he sees P illuminated is much smaller than with the light source L_e. Owing to the unevenness of the road surface, which as already stated includes surfaces giving regular reflection in all directions the point by point reflection of a punctiform light source L_p and its mirror image L_s will also be frequently visible to the observer as an elongated illuminated band. This is also the case with a light source L_e elongated in the vertical plane, although the contiguous points of this bright band will now have a lower brightness in the direction of the observer. A lighting unit consisting of a combination of lamp and light source expanded both laterally and vertically will therefore distribute the perceptible reflection over larger surfaces on a road surface with many areas giving regular reflection, and at the same time reduce the otherwise dazzling brightness.

The sharply-defined and trying reflection of long bright bands of pronounced brightness obtained in wet weather, beside which the rest of the traffic lane appears a deep black, should therefore be avoided as far as possible when the light source and the lamp together form a large radiating surface. This desirable effect is, however, not obtained when a vertical extension of the radiating surface is attempted by means of a specular reflector, and which produces points of intense brightness in the direction of vision. It is evident that when using a specular reflector the distribution of light and the path of the rays with a reflector of this type must be extremely carefully calculated and executed, and that furthermore a reflector of optimum design requires the most careful mounting in order to exclude disturbing points of brightness in the direction of vision of the road user. On the other hand, when selecting a diffusing reflector to give a specified light distribution, the fact that the above advantages must be foregone will be found in practice to be of comparatively small importance.

THE ENLARGED PROJECTION OF TELEVISION PICTURES

By M. WOLF.

Summary. An arrangement is described for the reproduction of television pictures in which the image on the fluorescent screen of a small cathode ray tube is projected on a ground glass screen measuring up to 1 × 1.20 m.

Introduction

The reproduction of television pictures by means of standard cathode-ray tubes has already been described in several previous articles which have appeared in this Review [1]). The pictures reproduced in this way on the fluorescent screen are, however, so small that it is difficult for an audience of more than a very few persons to view them conveniently at the same time. To facilitate viewing, larger tubes have been devised with a screen diameter of 40 cm, but in arriving at dimensions of this order a variety of difficulties are met with in the construction of the tubes, which become almost insurmountable when the dimensions of the tube are still further increased.

In particular, the screen end of the tube has to be given an increasing curvature as the diameter is itself increased, so as to prevent the tube collapsing under the pressure of the external atmosphere. But by increasing the curvature the edges of the television picture become distorted, and since this distortion increases with the distance from the axis of the tube, the area on the screen over which a television picture can be reproduced satisfactorily is limited by the distortion regarded as permissible in the picture. The flattest screen surfaces which can be produced technically without requiring an excessive thickness of glass are shown in *fig. 1* for screens of different diameters. Since it is only desired to bring out the difference in curvature of the screen ends of the tube, the tubes although having different diameters are here shown of the same size.

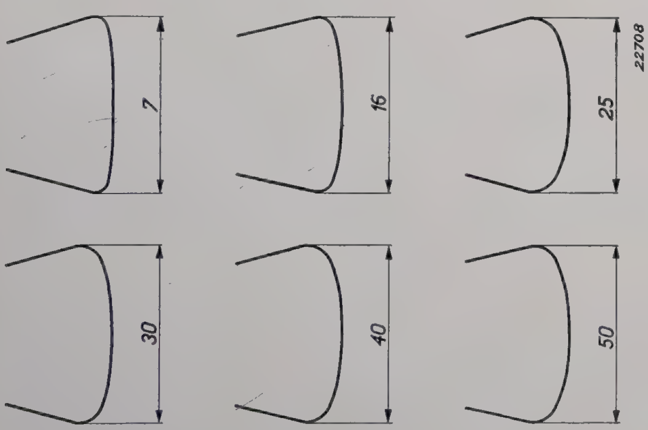


Fig. 1. Contours of several cathode ray tubes of different diameters showing the least curvature of the screens which can be tolerated from the standpoint of glass technology.

The adoption of very large tube-diameters is further limited by the fact that the precautions which have to be taken to obtain a robust tube not liable to collapse become rapidly more onerous as the diameter is increased.

In this connection, it may also be noted that the cost of making a tube increases so rapidly with the diameter of the screen that a large cathode-ray tube becomes altogether too expensive for use in television receivers.

The disadvantage of the extremely small picture normally obtained on the fluorescent screen can be remedied by making an enlarged projection of this picture. Projected television pictures of satisfactory definition and brightness measuring up to about 100 by 120 cm can be obtained by using small high-power television tubes in conjunction with a suitable optical system for enlargement. In ordinary rooms where the space available for an audience is comparatively small, the size of the projected picture should not exceed 40 by 50 cm. The best distance from which to view the projection screen is between five and ten times the width of the picture. Larger pictures are liable to be too large considering the space available in the average room.

A brief description is given in this article of the television tubes designed for projection purposes and of the optical means employed to make the best use of the radiation output of the television tube.

Television Tubes for Picture Projection

An optical system with the largest practicable relative aperture is required for the projection of television pictures. To avoid very expensive optical arrangements, the diameter of the picture must be made small and in practice the diameter of the image on the fluorescent screen should not exceed 8 cm.

It follows, therefore, that the sharpness of the focal spot of the electron beam has to conform to exceptionally severe requirements. With a screen raster of 405 lines the maximum diameter of the

[1]) Philips techn. Rev., **1**, 16 and 321, 1936; **2**, 33, 1937.

spot must not exceed 0.1 mm. This necessitates high anode voltages with which a focal spot of small diameter is much easier to obtain [2]) and which in particular allow a considerable amount of energy to be converted to light on the fluorescent screen. The Philips projection tubes are run on a voltage of between 20 to 25 kilovolts.

Electrostatic or magnetic lens systems can be used with equal effect for focusing the electron beam. Experience has shown that with magnetic lenses great sharpness can be obtained more easily than with the electrostatic system, because *inter alia*, a smaller number of electrodes is needed. This is an important advantage, since a system of electrodes which must be capable of dealing with a working voltage of 25 kilovolts has to be accommodated in a relatively confined space. For these reasons magnetic focusing has been adopted in the projection tubes developed by our laboratory.

The construction of a projection tube of this type is shown diagrammatically in *fig. 2.* On the front

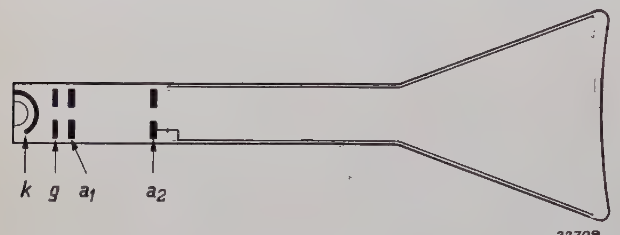


Fig. 2. Diagrammatic section of the projection tube. k - Cathode; g - grid; a_1 - first anode; a_2 - accelerating electrode.

surface of the grid g there is a small circular aperture behind which is the flat surface of the cathode k which is coated with an emissive material. The electrons are drawn out of the cathode by the first anode a_1, which also has a small aperture co-axial with the aperture in the grid; the final velocity is imparted to the electrons by the accelerating field between the first and the second anodes. This second anode a_2 is connected with a conducting surface which completely covers the inner wall of the tube between the anode a_2 and the fluorescent screen. No electric field exists in the space between a_2 and the conducting layer, apart from the comparatively small voltage drop produced at the screen by bombardment with the beam electrons. Between the anode a_2 and the conical part of the bulb is situated the magnetic focusing field, which is generated by an ironclad coil provided with an air gap. Owing to this air gap in the iron sheath the external magnetic field is restricted to a short region located just behind a_2. The magnetic fields for deflecting the electron beam are located also in this section of the tube.

A projection tube for use with a television receiver is shown in *fig. 3.*

The current intensity of the beam is mainly determined by the voltages at the grid and at the first anode, the field of the second anode penetrating only very slightly to the cathode. The system comprising the cathode, grid and first anode operates on exactly the same lines as that in a triode. Normally the voltage of the first anode is 250 volts with respect to the cathode; with a negative grid bias of about 40 to 50 volts the electron beam is then completely suppressed, while the current intensity of the beam at zero grid potential ($V_g = 0$) is 400 to 800 milliamps.

The current characteristic of the beam for a projection tube with 250 volts first anode voltage and 20 kilovolts at the last anode is shown in *fig. 4.*

The Optical System

A) Projection Lens

To project the image obtained on the fluorescent screen, it is desirable to use an optical system with the largest practicable relative aperture and also from reasons of cost to make the focal length of the projection lens as small as possible. But reduction of the focal length of the lens is limited, since the image on the screen to be projected by the lens is 8 cm in diameter, and the projected picture must have sharp definition right up to the edges.

To enlarge the area of sharp definition, an artifice was adopted in designing the projector tube. With lens systems of large aperture, the area of sharp definition of a flat object is principally limited by curvature of the image surface and only to a small extent by other optical defects due to using large angles of incidence. To produce a plane image on the projection screen, the fluorescent screen with its image is given a curvature corresponding with the curvature of that part of the lens image surface covered by the picture; in this way it is possible to reproduce a much larger area with high definition than when using a flat fluorescent screen. In general the screen is given such a curvature that the centre of curvature is located on the same side as the lens. For this reason the base of the projection tube has been made concave inwards, which is just the opposite to the shape adopted in standard cathode-ray tubes. Owing to the comparatively small diameter of the screen end a bulb of this type can be quite readily made without any loss in mechanical strength.

[2]) Philips techn. Rev., **1**, 33, 1936.

Fig. 3 shows clearly the concave shape of the screen end of the tube.

By using tubes with screens of the correct shape television images of 48 by 55 mm have been projected with satisfactory definition over the whole surface on to a flat screen of 40 by 50 cm, using a projection lens with a relative aperture of 1/1.9. With plane surfaces of projection, pictures of not more than 45 mm in diameter could be projected with sharp definition using this optical system.

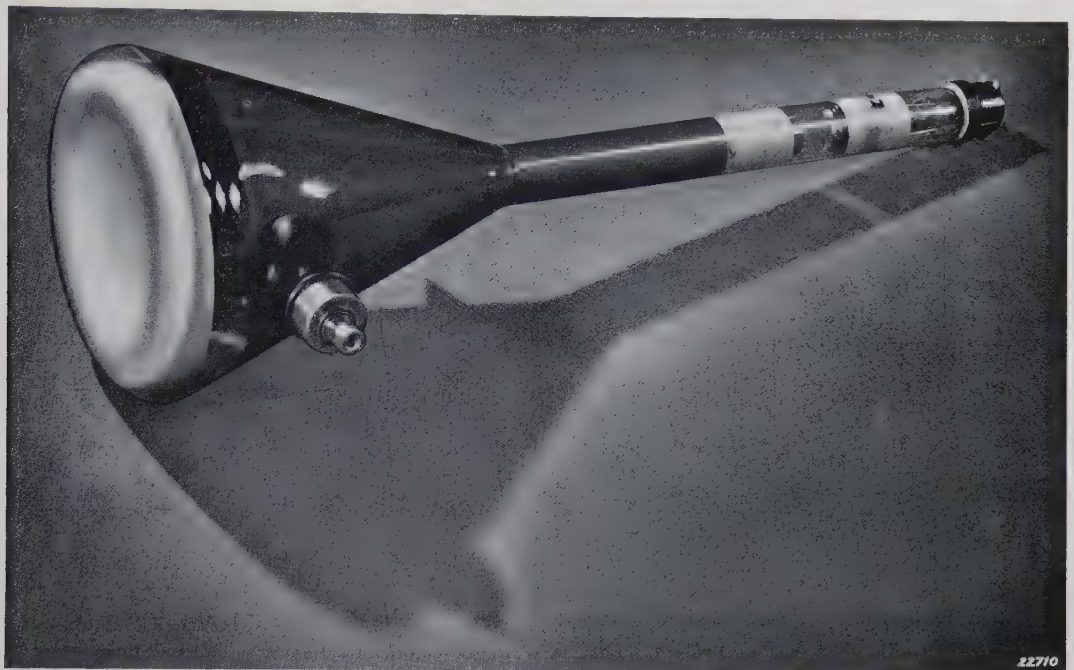


Fig. 3. Projection tube with concave screen surface.

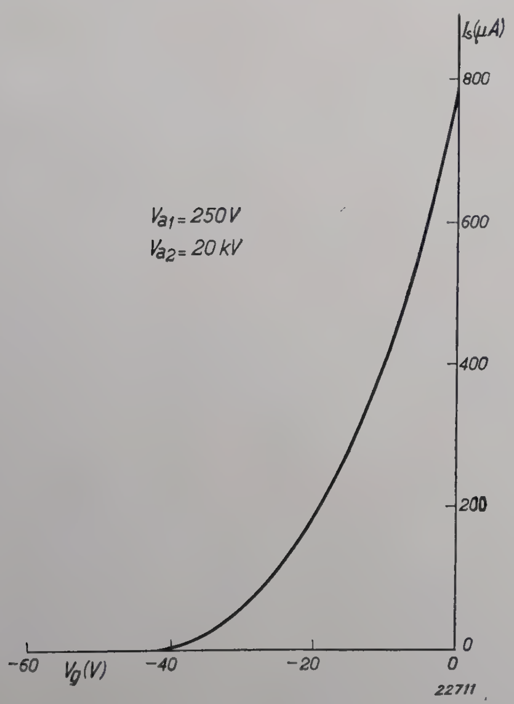


Fig. 4. Beam current plotted against grid voltage.

B) Projection Screen

The quantity of light transmitted in projection by a lens of this type is however, very small. If the efficiency of the optical system is defined as the ratio of the flux concentrated by the lens over a specific element of the picture surface to the total flux emitted by the corresponding surface element of the object, then analysis of the above-mentioned optical system would show an efficiency of only about 4 per cent. This result can be readily checked by calculation, if it is remembered that the radiation of the fluorescent layer in its immediate neighbourhood obeys Lambert's law and if the absorption and reflection losses in the optical system are also taken into consideration.

It is evident that the amount of light transmitted by the optical system must be utilised to the greatest effect. If the picture is projected on a diffuse-reflecting wall obeying Lambert's law, the brightness of the projected image with a tenfold enlargement may only be 0.0004 times the brightness on the fluorescent screen. Since the illumination of the fluorescent screen is of the order of 10^4 to $2 \cdot 10^4$ lux [3]), the brightness of the projected image will only be about 4 to 8 lux. To increase this value, it is essential to use screens having more or less specularly reflecting or translucent surfaces which possess lower dispersion values than represented by

[3]) The illumination in lux is defined as the illumination obtained on a white screen with reflecting properties obeying Lambert's law when it is illuminated with an intensity of the same number of lux.

Lambert's law. The use of specularly reflecting screens is impracticable in view of the comparatively short distance separating the optical system and the screen (short focal length): there would then be hardly room to accommodate the audience between the projection lens and the viewing screen. The second method, however, offers various important advantages. In this case the short distance separating the projection lens and the screen is an advantage since it enables the cathode-ray tube, the lens and the projection screen to be incorporated in a single housing, so that the total path of the light rays between the object and the image is confined to the interior of the receiver. Apart from the apparatus itself, no other components have then to be set up separately and the space available on the viewing side of the screen is unrestricted.

A ground glass sheet is used as the translucent screen. If a narrow pencil of parallel rays falls on one side of a screen of this type, the light will be dispersed by the matt surface so that on the other side of the screen rays will be projected on the viewer's eye not only when the viewer is located in the same straight line as the incident beam, but also when the line joining the viewer's eye with the point of incidence of the light ray on the screen is inclined to the normal. The dispersion produced by a particular screen can be represented diagrammatically by indicating the brightness in each direction by the length of an arrow drawn in that direction. The line joining the heads of the arrows then represents the dispersion curve of the particular screen. The curves for two ground glass screens with different degrees of roughness are reproduced in *fig. 5* drawn to the same scale.

It is obvious that with a small dispersion curve as shown in fig. 5*a* the brightness dispersed directly to the front with equivalent illuminations will be greater than with a dispersion curve of the type shown in fig. 5*b*, since under the conditions shown in curve *a* the energy incident on the rear side is mainly projected straight ahead. Dispersive screens can therefore be characterised by the intensity of light transmitted directly to the front. It is interesting to compare this intensity with that obtained in dispersion according to Lambert's law and to define the ratio of these two intensities as the intensification of the dispersive screen. With the majority of ground glass screens this intensification is very high, and in the cases illustrated in fig. 5 it is 9.9 for *a* and 4.6 for *b*.

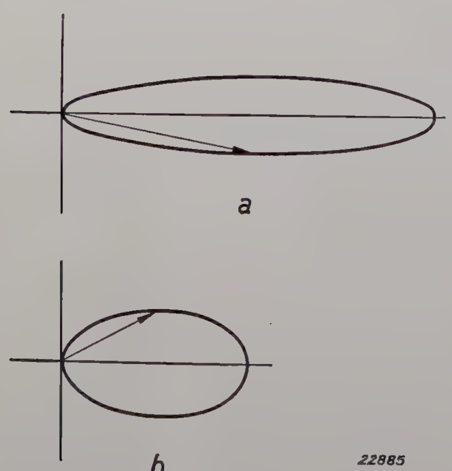


Fig. 5. Dispersion curves for two ground glass screens with different degrees of roughness. Screen (*a*) with the lower dispersion is the more suitable.

The use of screens with a minimum dispersion curve is limited by the fact that the middle and the edge of the projected image must not reveal excessive differences in brightness to an observer looking along the axis of projection, and also since the brightness must not diminish too much when the viewer moves out of the axis of projection, otherwise the area within which the picture can be viewed distinctly and comfortably will be too small.

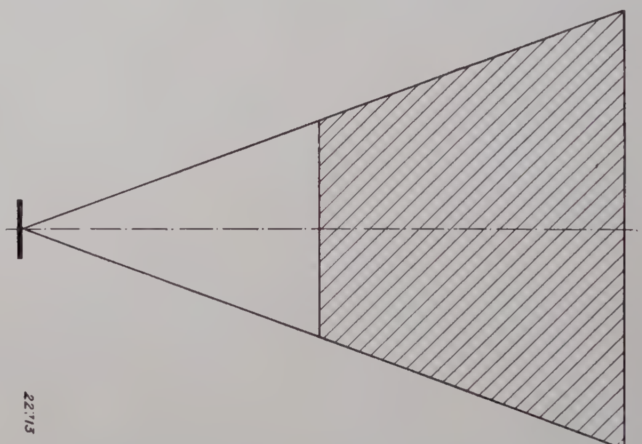


Fig. 6. Effective area (shown shaded) for satisfactory viewing of television pictures.

A serviceable middle course must therefore be found between these adverse and favourable features, and experience has shown that the screen whose dispersion curve is of the type given in fig. 5*a* provides a satisfactory compromise. Practical experience in the projection of films indicates that the permissible differences in brightness are fairly high: brightness differences of 50 per cent are only rarely obtained. This accounts for the satisfactory results obtained with the comparatively very small dispersion curve shown in fig. 5*a*. The area within which a good view of the projected picture is obtained is roughly bounded by two lines drawn from the middle of the screen at an angle of about 20 deg.

to the axis of projection and by the above-mentioned maximum or minimum distances from the screen, thus giving a trapezoidal area of about 8 sq. m with a picture measuring 40 by 50 cm.

In *fig.* 6 the viewing area is indicated by shading. Outside this area viewing is also quite satisfactory although under slightly less ideal conditions. The intensity of illumination over the bright areas of the picture is about 30 to 60 lux, which is quite adequate for television reception in rooms of moderate illumination. Two photographs of television pictures projected on ground glass screens are reproduced in *fig.* 7; these may be compared with those already published in Philips techn. Rev. **1**, 325, 1936, which show the images thrown on the fluorescent screen of a standard cathode ray tube.

Fig. 7. Television pictures thrown on to ground-glass projection screens, 40 by 50 cm in size; total lines 405 and interlaced scanning.

PRACTICAL APPLICATIONS OF X-RAYS TO THE EXAMINATION OF MATERIALS. XII

By W. G. BURGERS.

24. Non-Ideal Crystals

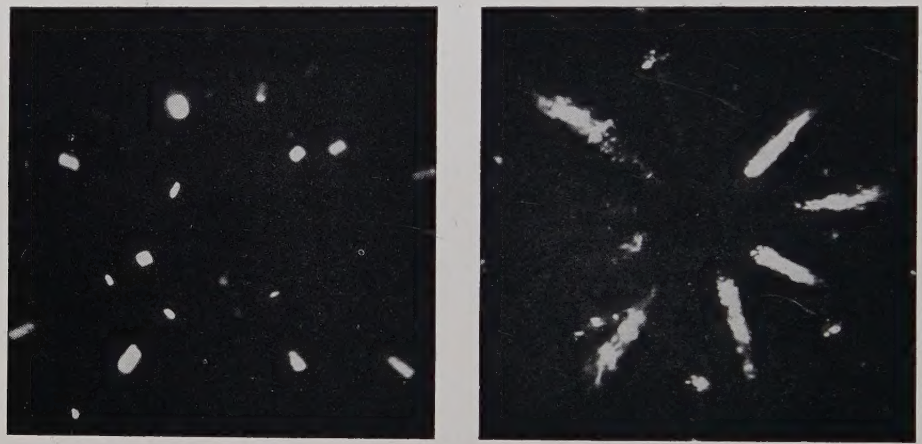
Example: The Diamond

It has been frequently stated that the diffraction of X-rays produced by crystals can be interpretated as a reflection of the rays at the surfaces formed by the atoms composing the crystal, the radiation being reflected in exactly the same way as light rays by an ordinary mirror.

It is evident that the reflected rays are confined in one direction of reflection only when the reflecting lattice surfaces are plane; this is actually the case with undistorted crystal lattices. But in many or in the different crystallites from which the substance is built up; in some cases these surfaces may be more or less distorted.

It is obvious that all such deviations in the lattice must cause the X-rays to be reflected in directions which will differ somewhat from the direction of specular reflection obtained with normal and undistorted crystals. In the X-ray photogram this will lead to either a broadening or a weakening of the reflected beam which in specific cases may

a



b

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Fig. 1. Diffraction patterns of natural diamond.
a. Colourless stone, with undistorted crystal lattice.
b. Cloudy stone, with distorted lattice built up of a large number of units with slightly-different mutual orientations (mosaic crystal).

cases the lattices are not in this ideal condition.

In the first place, naturally-grown crystals are frequently not ideal but built up from a large number of blocks in different orientations varying by not more than a few degrees; these arrangements are referred to as mosaic crystals. The divergence of these crystals from an ideal structure may be the result of the conditions of growth; for instance a truly parallel growth of the crystal surfaces may be rendered difficult by crystallisation taking place too rapidly.

Secondly, deviations from an ideal lattice structure may be due to mechanical strains. Owing to the resulting internal strains, equivalent lattice surfaces will then no longer be spaced at exactly the same intervals apart throughout a crystal be shown in very different ways in the diffraction patterns. If the preparation under examination consists of a single crystal, which whould give a pattern with a comparatively small number of spots (Laue pattern), these spots in the case of a distorted crystal will become expanded to bands of different lengths, similar to the distorted image obtained in a curved mirror. If the material under examination has a fine-crystalline structure whose interference pattern consists of a large number of small spots which coalesce to form continuous haloes if the crystallites are sufficiently fine (Debye-Scherrer pattern), these haloes will become blurred or broadened when the individual crystallites are deformed by mechanical forces or from any other cause.

Examples of these phenomena in fine-crystalline materials have already been given in article No. VIII of this series [1]). *Fig. 1* in the present article reproduces two X-ray photograms obtained with natural diamonds, *a* being that of a colourless stone and *b* that of a cloudy stone. The difference in character of the spots obtained by reflection of the X-rays at the crystal surfaces is evident. The expanded bands in *b*, which are composed of separate small spots, indicate that the cloudy stone in comparison with the colourless one, is built up of a mosaic of not perfectly parallel crystal units. It is clear that this difference in structure will be apparent also in other properties of the stone (e.g. brilliancy and brittleness).

25. Detection of Very Small Crystals. Example of Zinc Sulphide Crystal-Size Variation

In addition to the above-described cause of line broadening in X-ray photograms, another cause may also exist. This may be due to the fact that the diffraction of X-rays, which is essentially an interference phenomenon, will be confined to a narrow range of directions only when the effects produced by a large number of atoms are in concert. Accordingly, even with an entirely undistorted crystal lattice, reflection will be confined to the normal direction of specular reflection only when the crystal in question has a definite minimum size (about 0.1 μ). If the preparation under examination is composed of smaller crystals the rays will also be diffracted in directions which deviate considerably from that of specular reflection. As a result, the reflected rays will be included within a certain solid angle which gives rise to broadened lines on the photogram.

As an example of these conditions, two photograms are reproduced in *fig. 2* for a zinc sulphide preparation which was precipitated from a solution of a zinc salt. In order to follow the change in certain physical properties, radiographs were made of the preparation after two different heat treatments, viz., after drying at 100 deg. (fig.2*a*) and after ignition for an hour at 500 deg. (fig. 2*b*). The lines in fig. *a* are distinctly widened, which indicates that the crystals of the deposited and dried zinc sulphide are smaller than about 0.1 micron, while the sharp lines in fig. *b* show that by strong heating to 500 deg. these small crystals have coalesced to form larger ones. The latter must, however, be less than 10 microns since at this dimension the continuous interference lines are resolved into separate spots, as may be seen from fig. 2*b* for recrystallised nickel tubes in article No. IX of this series.

The occurrence of blurred interference lines can, therefore, be due either to the presence of very small crystals or to crystals which are distorted by internal stresses, so that in each particular case both possibilities must be given due weight. It will not always be easy to determine with certainty which of these conditions (or even if both together) are responsible for the widening of the lines. A very difficult problem in this respect is presented by very finely-ground powder, since on grinding not only are the crystals reduced to very small dimensions but a deformation of the small crystals may also take place as a result of the mechanical forces applied during grinding. Crystals having a more or less abnormal lattice structure can also be readily produced when substances are rapidly precipitated, for example by rapid sublimation from the vapour phase; this factor must be taken into consideration when dealing with the precipitated zinc sulphide referred to above.

a

b

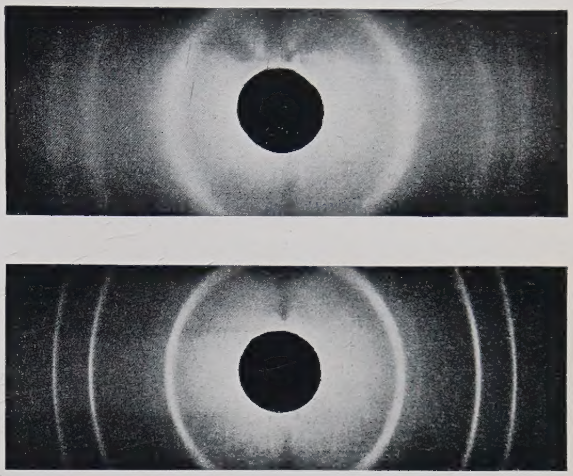

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Fig. 2. Diffraction patterns of zinc-sulphide precipitates.
a. After precipitation and drying at 100 deg. C.
b. After one hour's ignition at 500 deg. C.
The broadened lines in *a* indicate the presence of small crystals with dimensions of 1 micron. By strongly heating to 500 deg. these small crystals coalesce to larger crystals, as indicated by the sharpness of the lines.

26. Amorphous Bodies

To conclude this series of articles, brief reference must also be made to the diffraction of X-rays produced by non-crystalline or socalled amorphous bodies, such as glass, artificial resins, etc. It appears probable that in general no directional interference would take place with these bodies, since in amor-

[1]) Philips techn. Rev., **1**, 373, 1936.

[2]) Philips techn. Rev., **2**, 29, 1937.

phous substances the molecules are not arranged in a crystal lattice in the same way as in crystals. Interference patterns can, however, be obtained even with amorphous bodies, because also in these bodies, exactly as in liquids, the molecules are not as a rule entirely free from some kind of regimentation, but exhibit certain characteristics of a mutual orientation. In consequence, an amorphous body, insofar as the dispersion of an incident radiation is concerned, may be regarded broadly as a highly-deformed lattice in which a regular orientation is confined to very small groups each composed of only a few molecules.

From the above considerations regarding the effects of lattice distortion and of the extremely small dimensions of the crystals, it is not surprising to find that the diffraction patterns obtained with amorphous bodies and liquids consist of a single or a few comparatively diffuse interference haloes. In *fig. 3a* to *d*, four patterns of this type have been reproduced, viz., for two phenol and cresol-formaldehyde artificial resins. It is seen from figs. *c* and *d* that resins obtained by the polymerisation of different original molecules give distinctive patterns with marked differences in the diameters and definitions of the haloes. This is due to the difference in the size of the combining molecules and hence to their distances apart, as well as to their orientation in the polymerised product. Thus to a certain extent, substances with such ill-defined structures as the resins can be differentiated by their X-ray diffraction properties. The diffraction patterns in figs. *a* and *b* were obtained with the same resins in different stages of polymerisation. This difference is not brought out in the patterns-this is not surprising if it is remembered that as polymerisation proceeds the original molecules coalesce in increasing numbers, but always on the same plan, to form the polymerised structure; the orientation of and distances between the molecules are not altered during this building-up process.

The marked difference in the interference patterns obtained with amorphous and crystalline substances enables a specific preparation or material

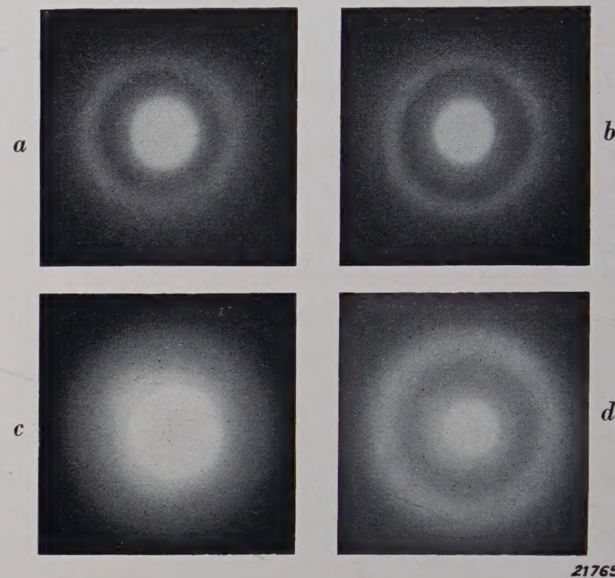

Fig. 3. Interference patterns of artificial resins.
a. Phenol-formaldehyde resin, slightly polymerised.
b. Phenol-formaldehyde resin, highly polymerised.
c. o-cresol formaldehyde resin.
d. p-cresol formaldehyde resin.

to be distinguished as crystalline or amorphous; this problem has an important application in practice, as for instance for determining whether certain precious stones are genuine or not. Stones prepared from glass may be readily distinguished by the appearance of one or more haloes in the interference pattern instead of the sharply-defined spots obtained with real stones, see e.g. the pattern in fig. 1*a* for diamond.